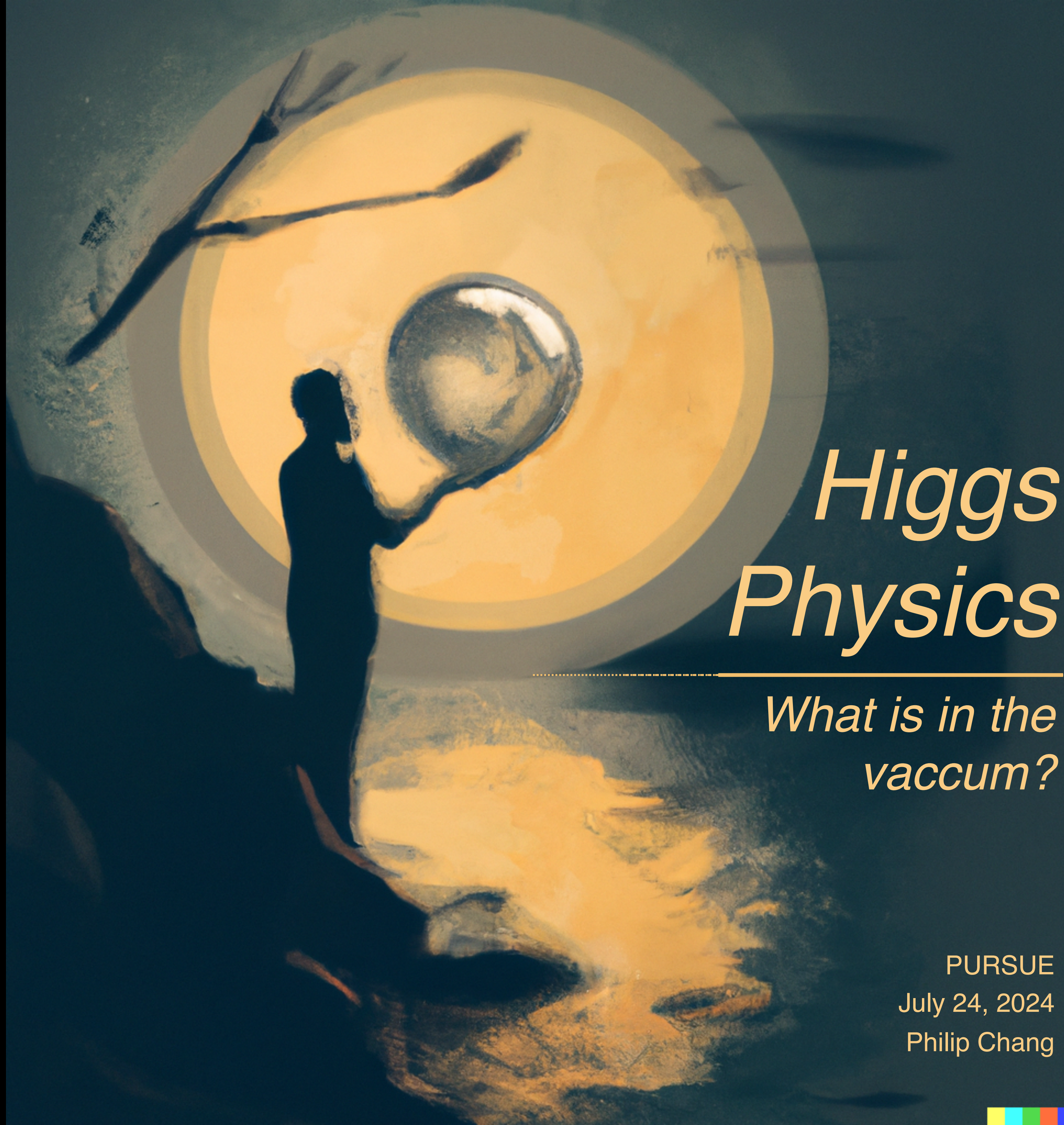


Higgs Physics

What is in the vaccum?

PURSUE
July 24, 2024
Philip Chang

Outline

UF
Chang
Florida

Why Higgs?

Higgs Discovery / Measurement

Higgs Future

Standard Model

Fermions (Matter)

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

← Spin 1/2 →

Bosons (Force carriers)

Gauge

Z	γ
W	g

← Spin 1 →

Higgs

H

↑ Spin 0

Standard Model

Fermions (Matter)

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

← Spin 1/2 →

Bosons (Force carriers)

Gauge

Z	γ
W	g

← Spin 1 →

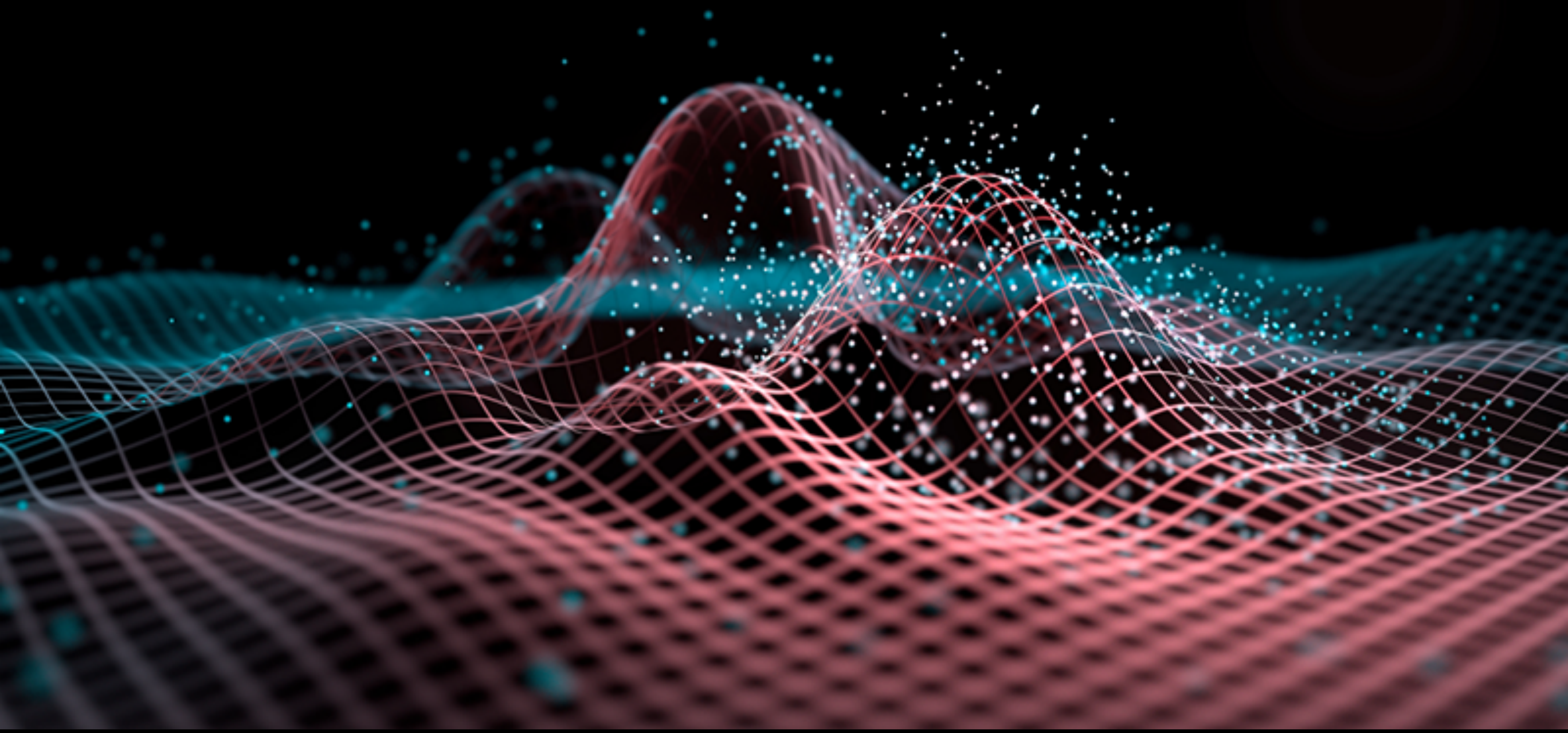
Higgs

H

↑ Spin 0

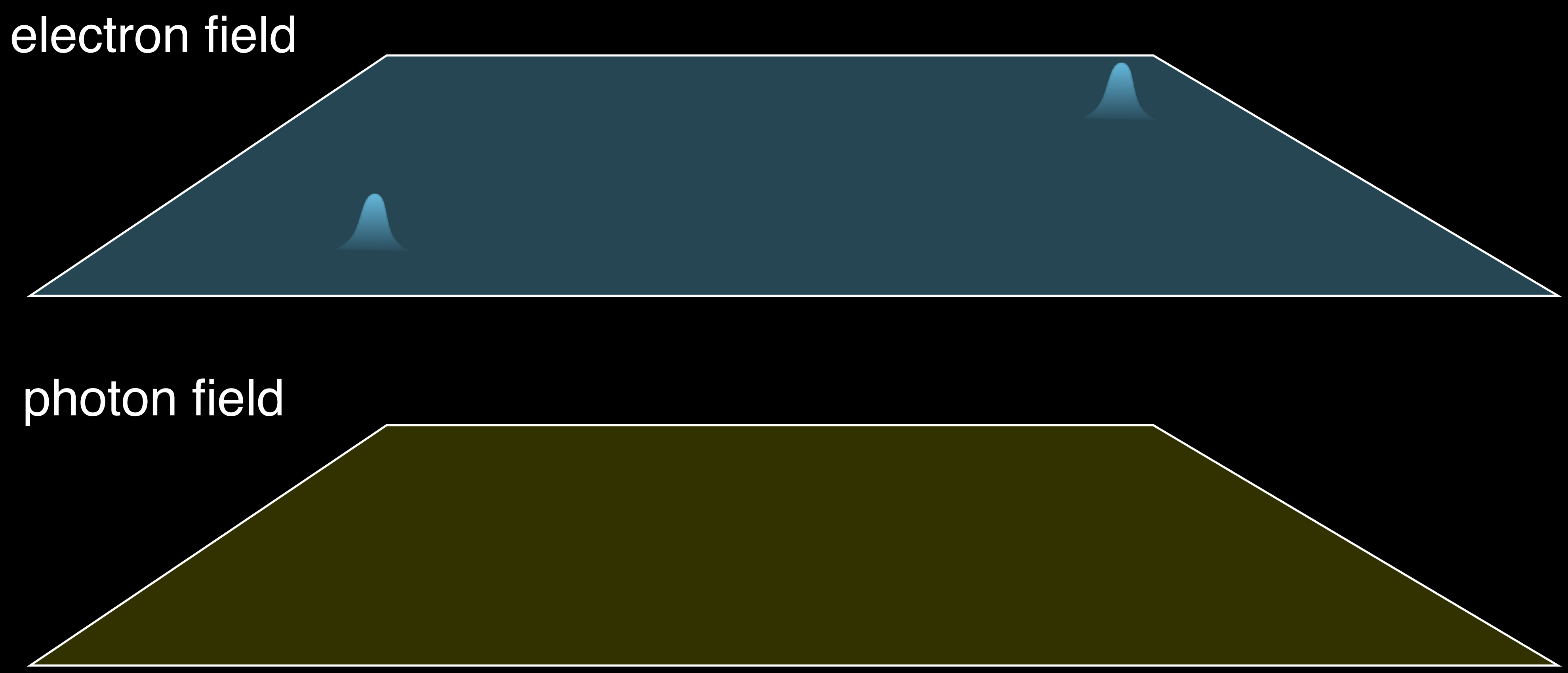
Why do we need Higgs in the SM?

SM is based on Quantum Field Theory



Credit: https://physics.aps.org/articles/v16/165

Quantum Field Theory



Quantum Field Theory

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Quantum Field Theory

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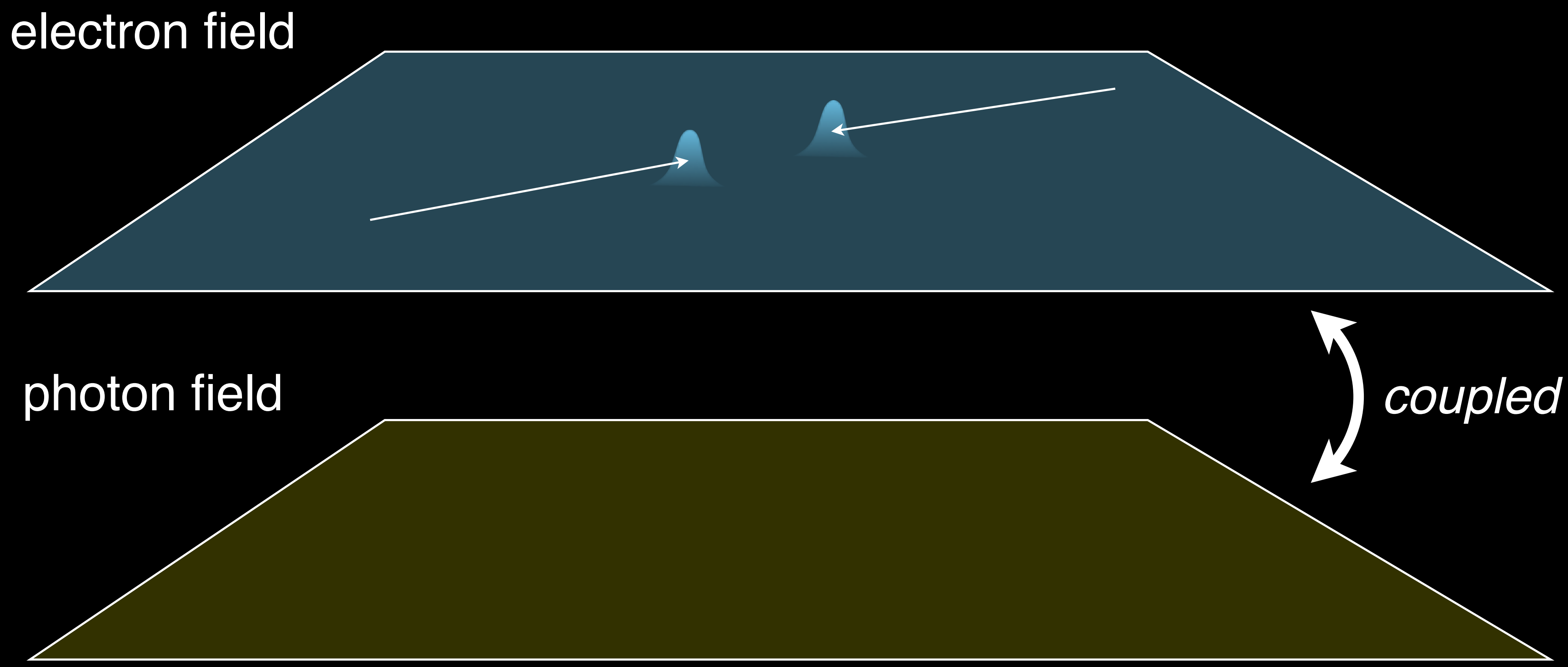
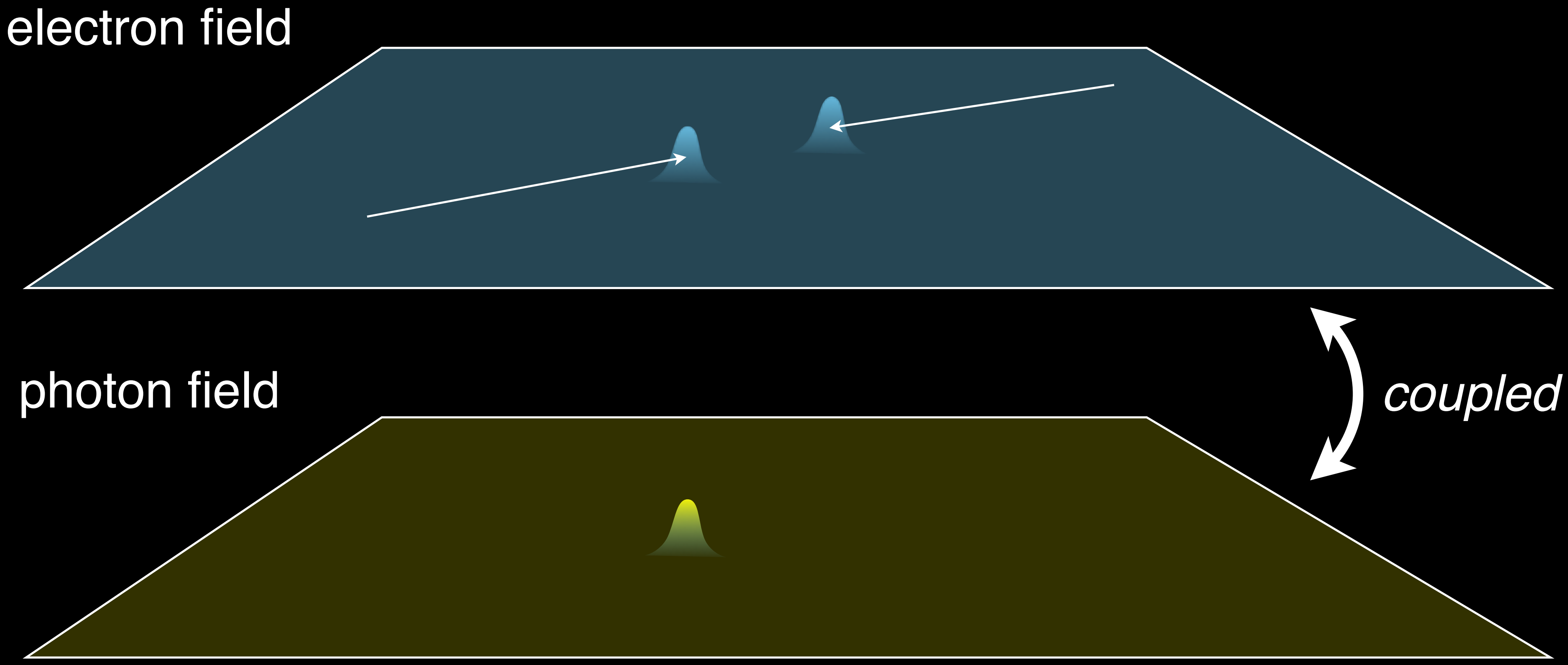
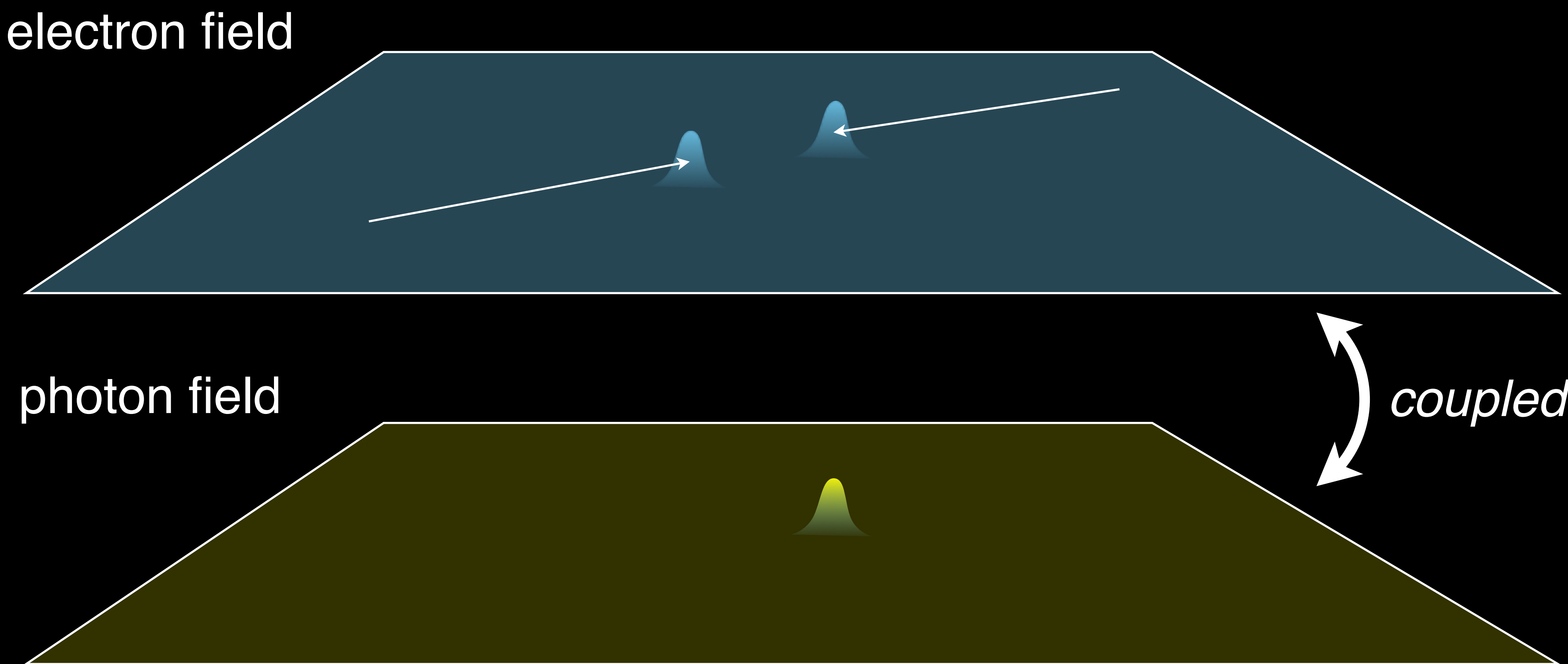


Quantum Field Theory



Quantum Field Theory



Quantum Field Theory

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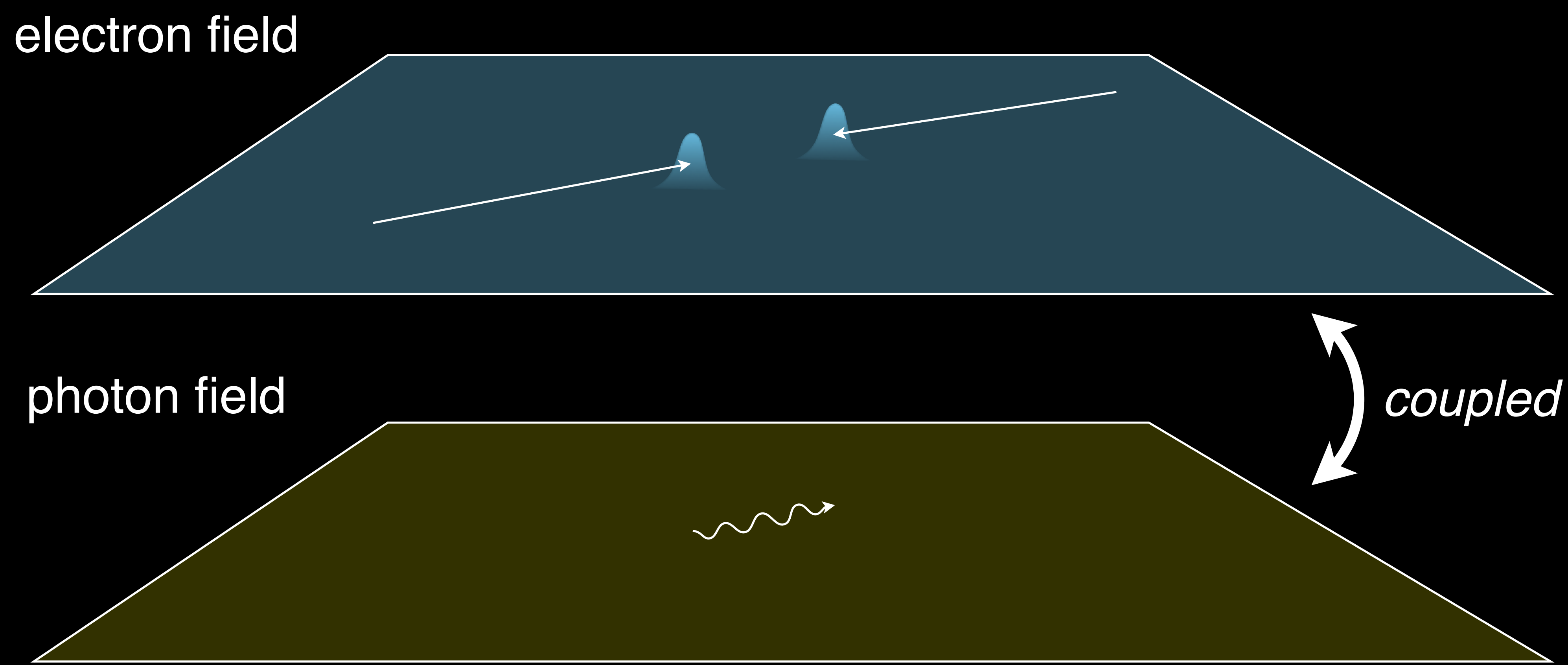

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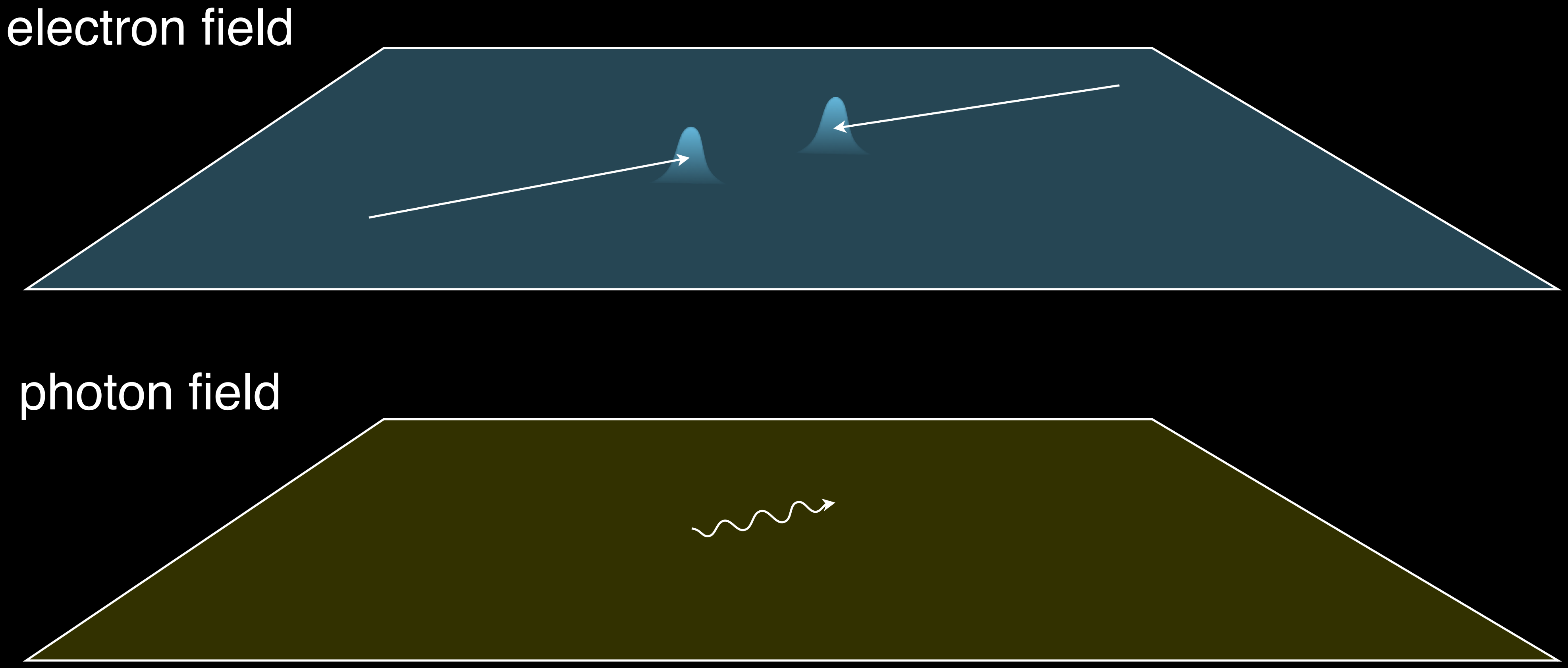
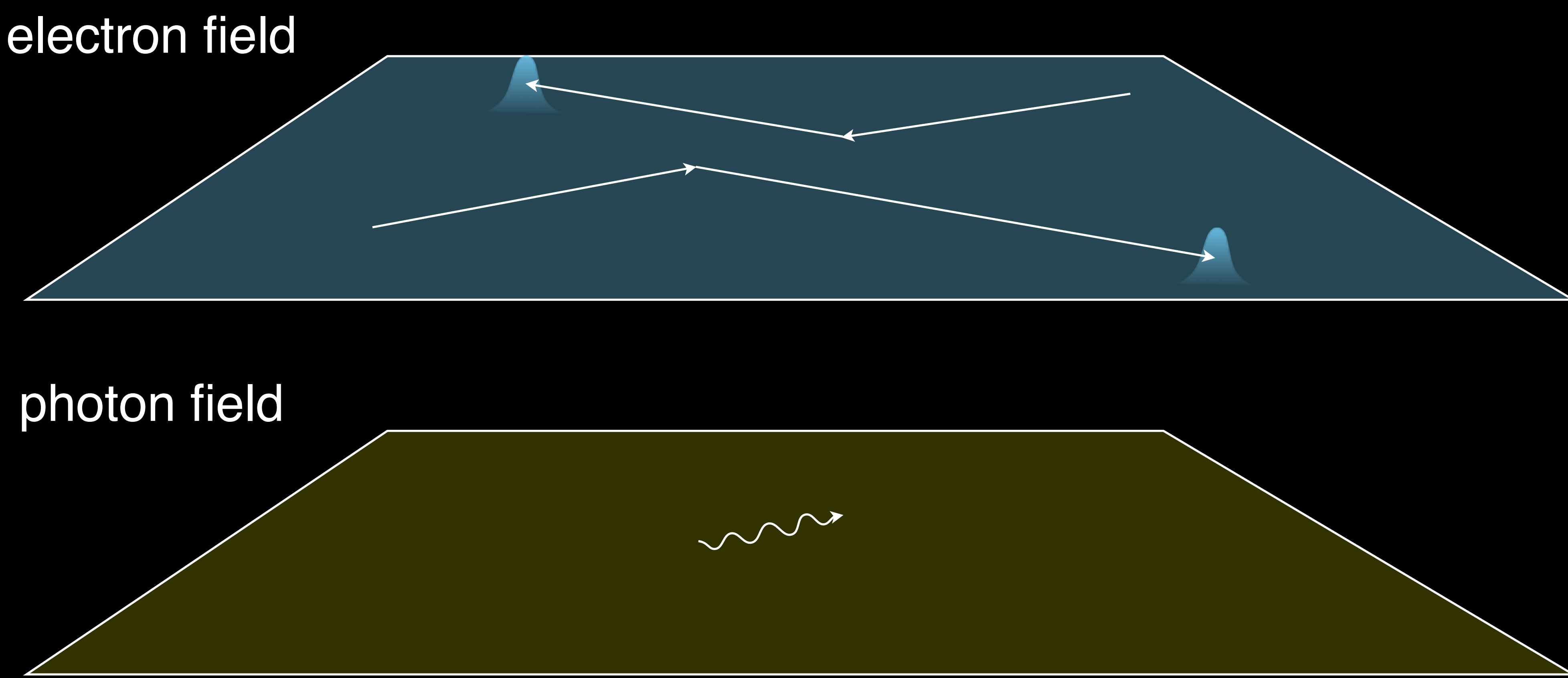


Quantum Field Theory



Quantum Field Theory

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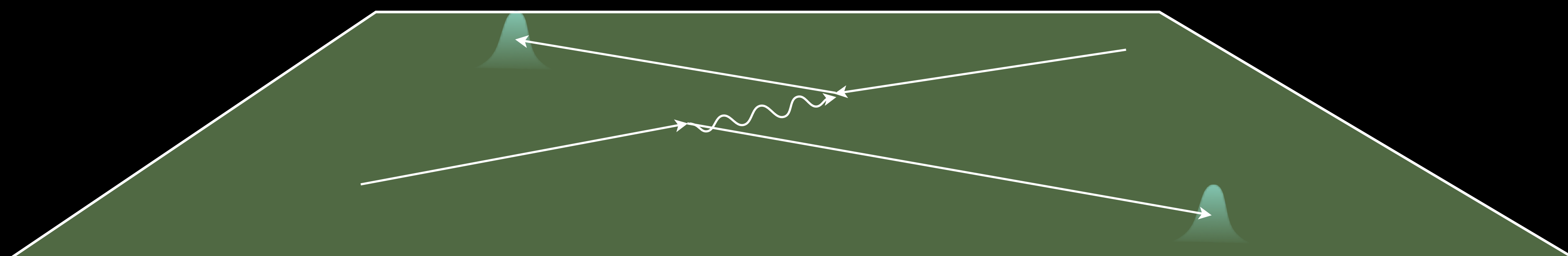
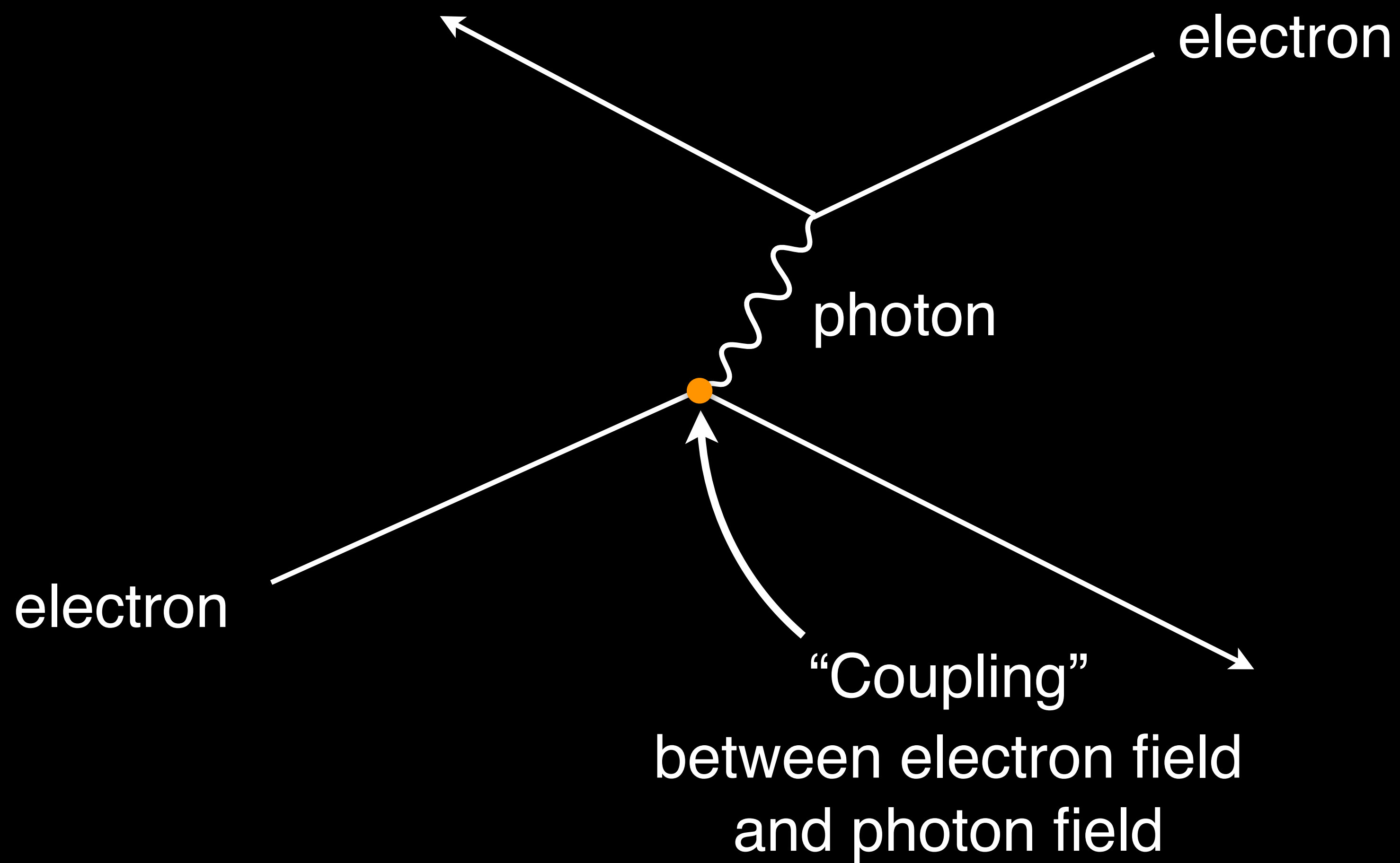
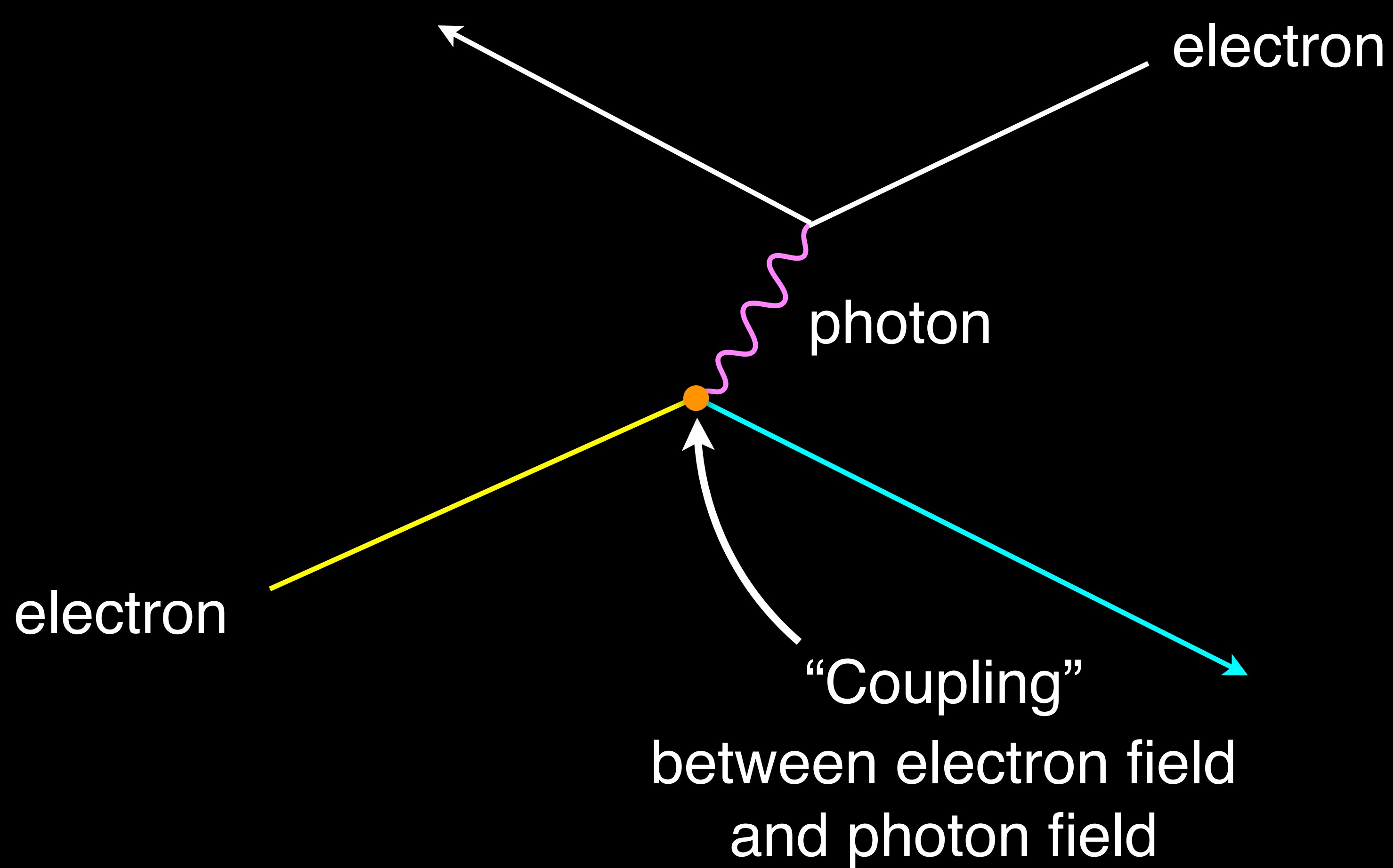


Feynman Diagram

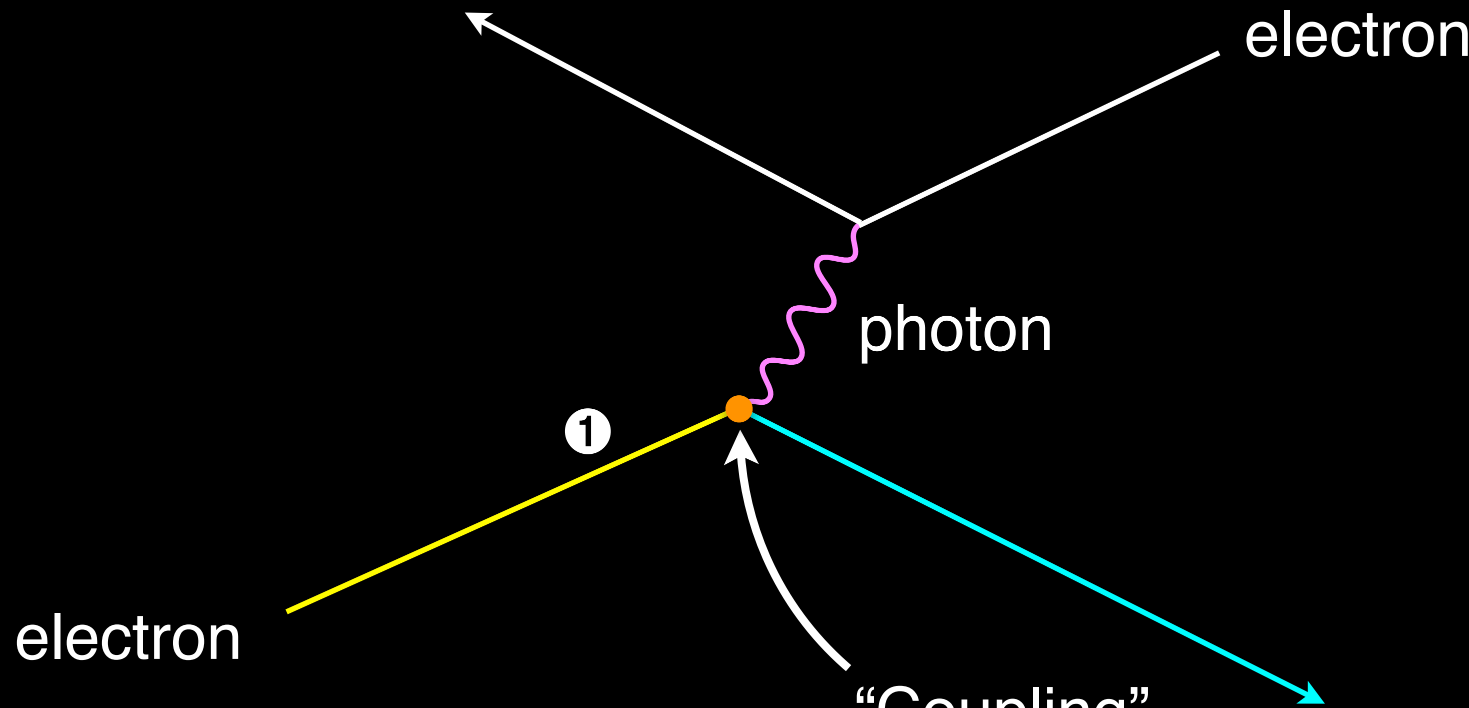


Feynman Diagram



$$e\,\bar{\psi}\,\gamma^{\mu}\,\psi\,A_{\mu}$$

Feynman Diagram

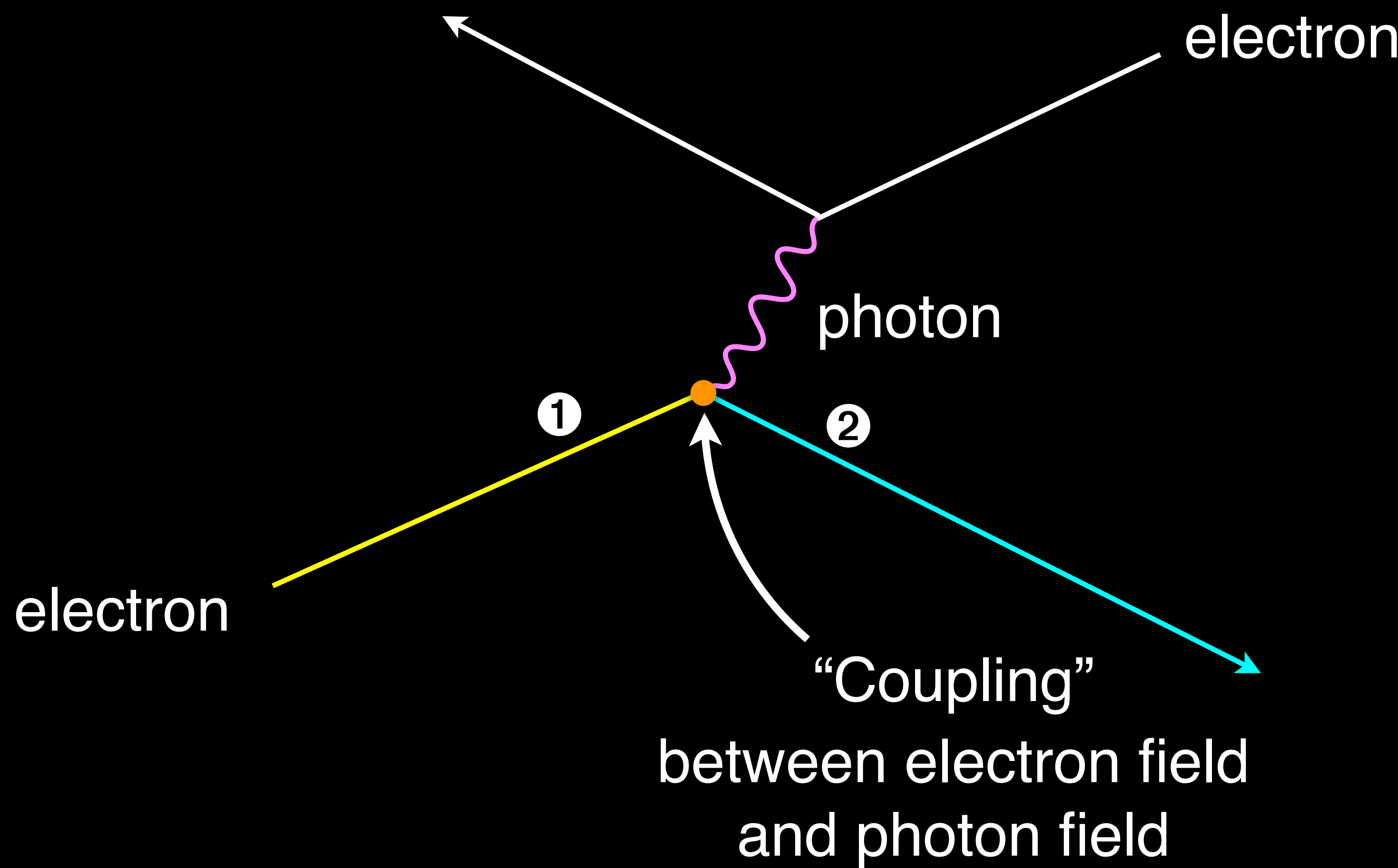


"Coupling"
between electron field
and photon field

$$e\,\bar{\psi}\,\gamma^{\mu}\,\psi\,A_{\mu}$$

❶

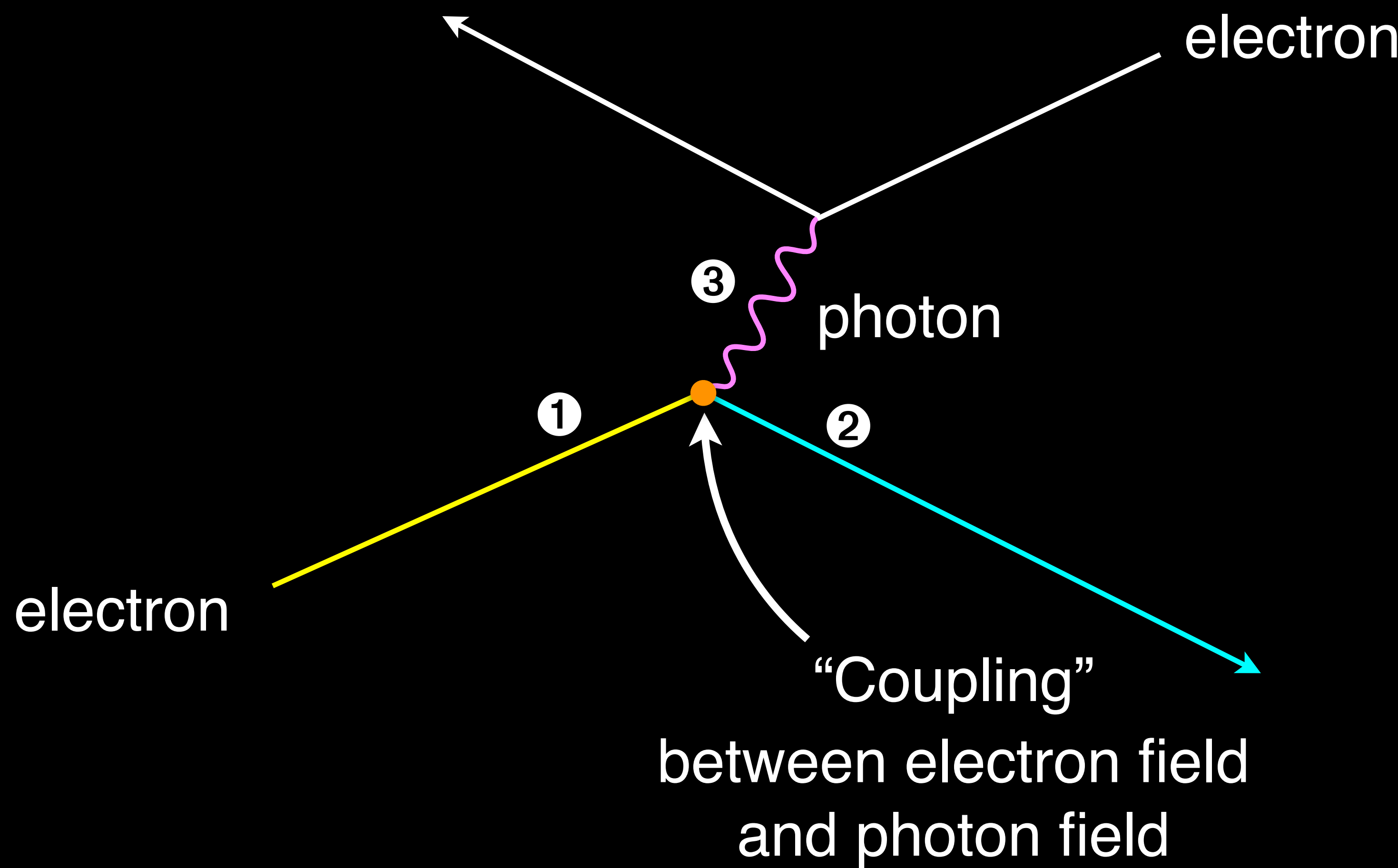
Feynman Diagram



$$e\ \bar{\psi}\ \gamma^{\mu}\ \psi\ A_{\mu}$$

➊ ➋

Feynman Diagram



$$e\,\bar{\psi}\,\gamma^{\mu}\,\psi\,A_{\mu}$$

❶ ❷ ❸

SM Lagrangian

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https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

SM Lagrangian

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SM Lagrangian

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$

$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$

$$\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$

$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$

$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$

$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$

$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$

$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$

$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$

$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$

$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$

$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$

$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$

$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$

$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$

$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$

$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$

$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$

$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$

$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$

$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$

$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$

$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$

$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$

$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$

$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

SM Lagrangian

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$

5

$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

SM Lagrangian

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2

$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$

3

$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] -$$

4

$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 -$$

5

$$\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- -$$
$$\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y -$$
$$\partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) - \frac{1}{2}gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] +$$
$$\frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] +$$
$$igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac{1}{2}igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

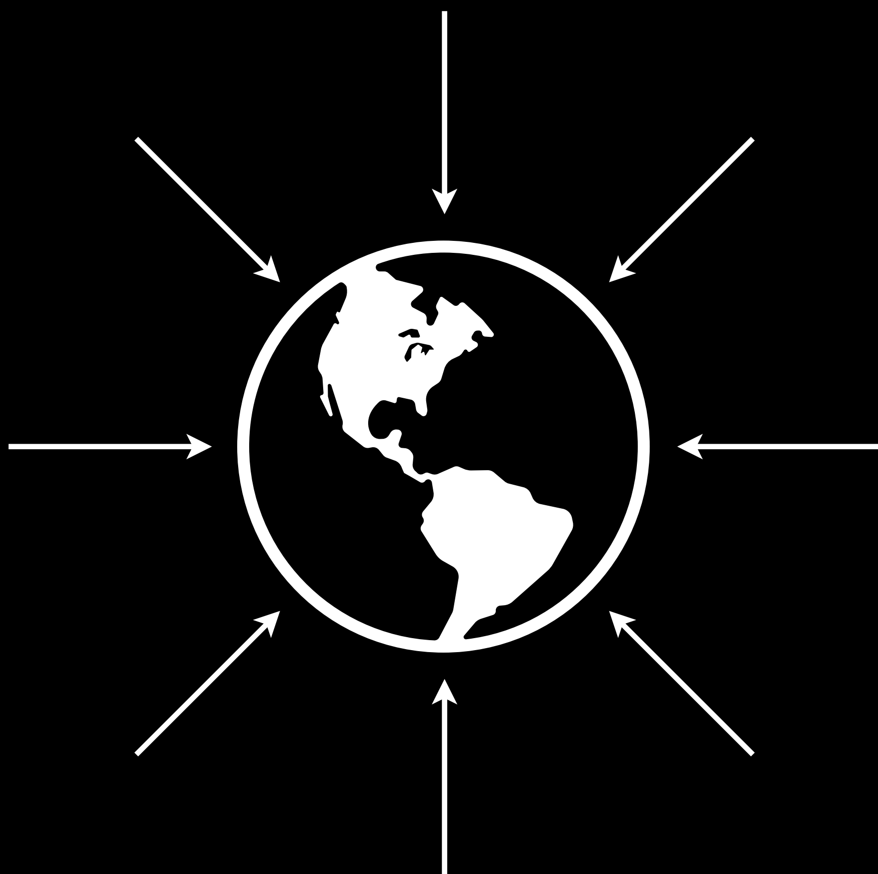
Symmetry

SU(3) × SU(2) × U(1)

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

What does it mean by symmetry?

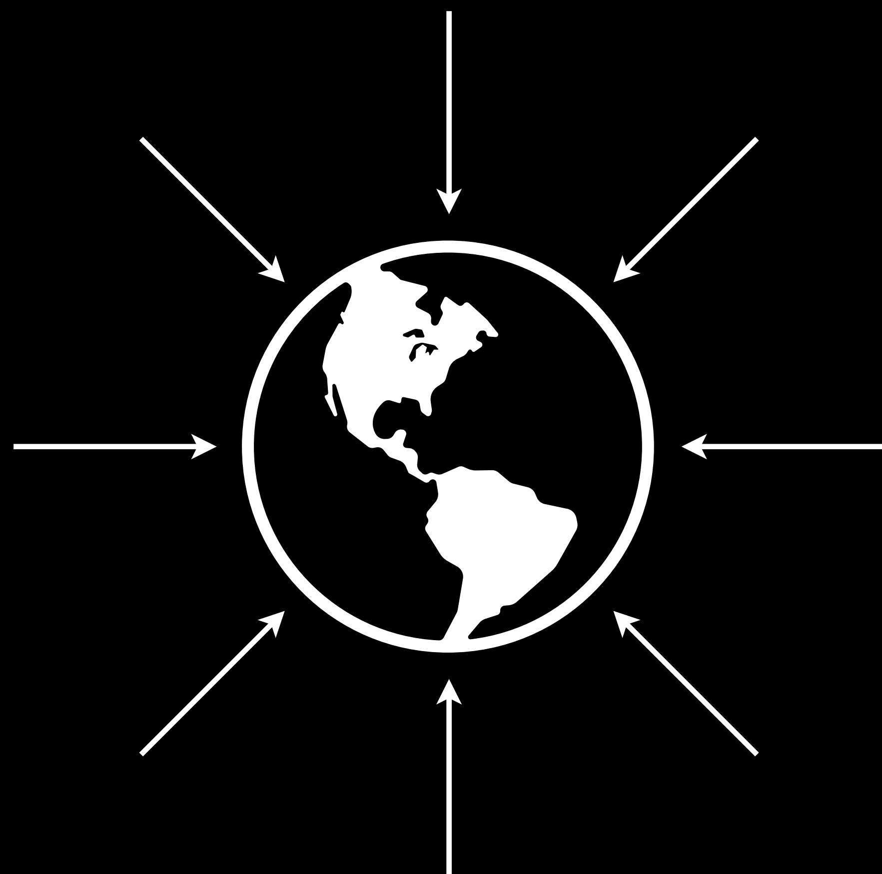
Take a simple classical mechanics example



$$F = -\frac{\partial}{\partial r} U$$

What does it mean by symmetry?

Take a simple classical mechanics example

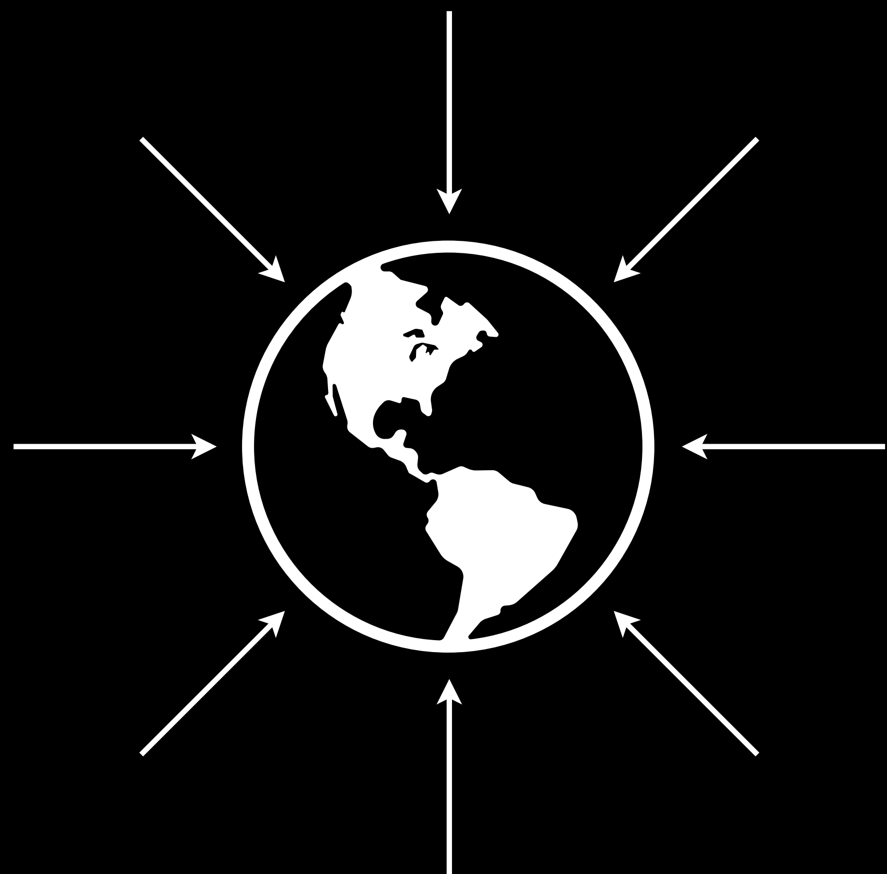


$$F = -\frac{\partial}{\partial r} U$$

U is not unique since I can always add a constant term

What does it mean by symmetry?

Take a simple classical mechanics example



$$F = -\frac{\partial}{\partial r} U$$

U is not unique since I can always add a constant term

$$U \rightarrow U + \alpha$$

What does it mean by symmetry?

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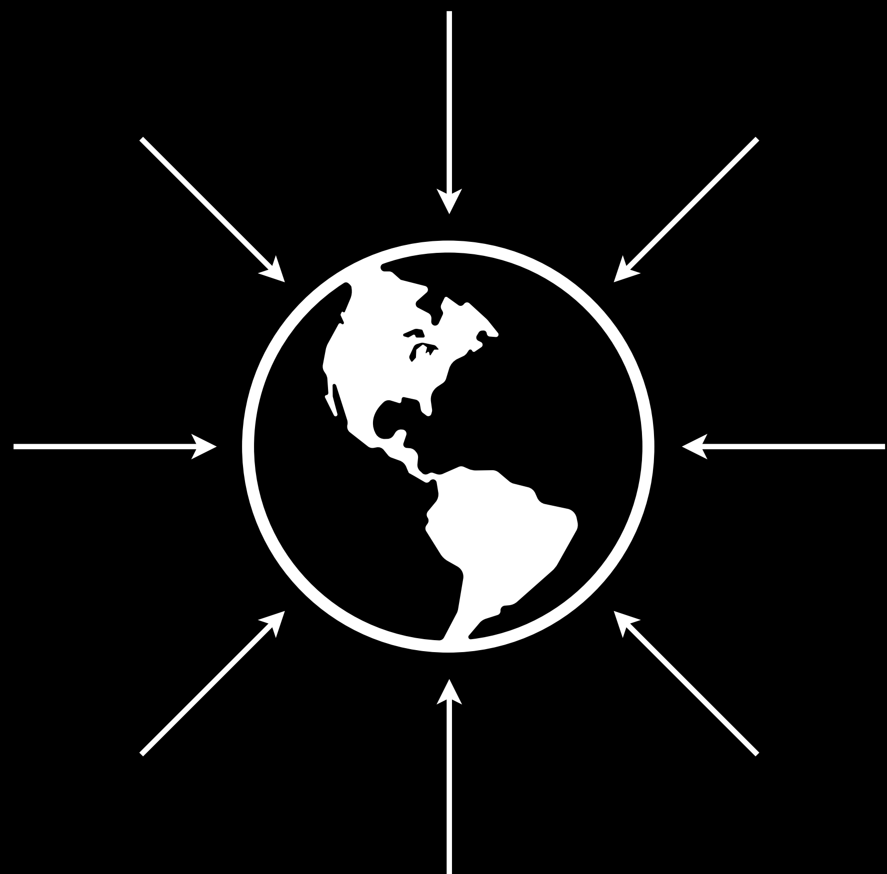
Take a simple classical mechanics example



$$F = -\frac{\partial}{\partial r} U$$

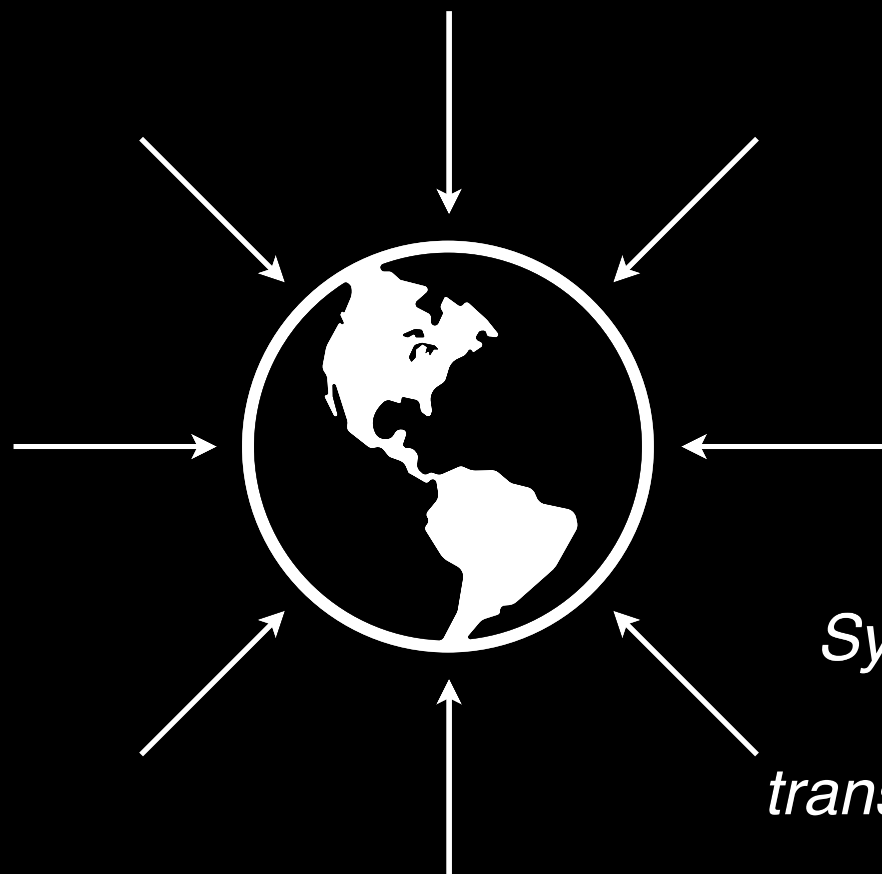
U is not unique since I can always add a constant term

$$U \rightarrow U + \alpha$$

Still $$F = -\frac{\partial}{\partial r} U$$

What does it mean by symmetry?

Take a simple classical mechanics example



$$F = -\frac{\partial}{\partial r} U$$

U is not unique since I can always add a constant term

Symmetric under transformation

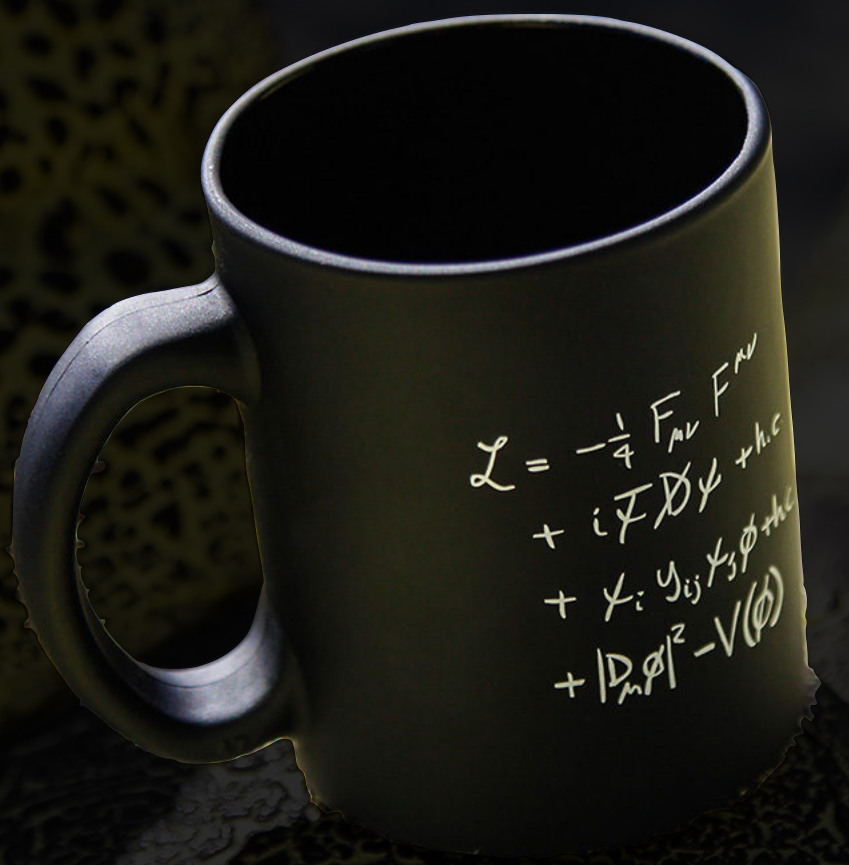
$$U \rightarrow U + \alpha$$

Still

$$F = -\frac{\partial}{\partial r} U$$

SM Lagrangian

SM Lagrangian



mass terms

$m \bar{\psi} \psi$	Fermions mass term
$m^2 V_\mu V^\mu$	Gauge Bosons mass term

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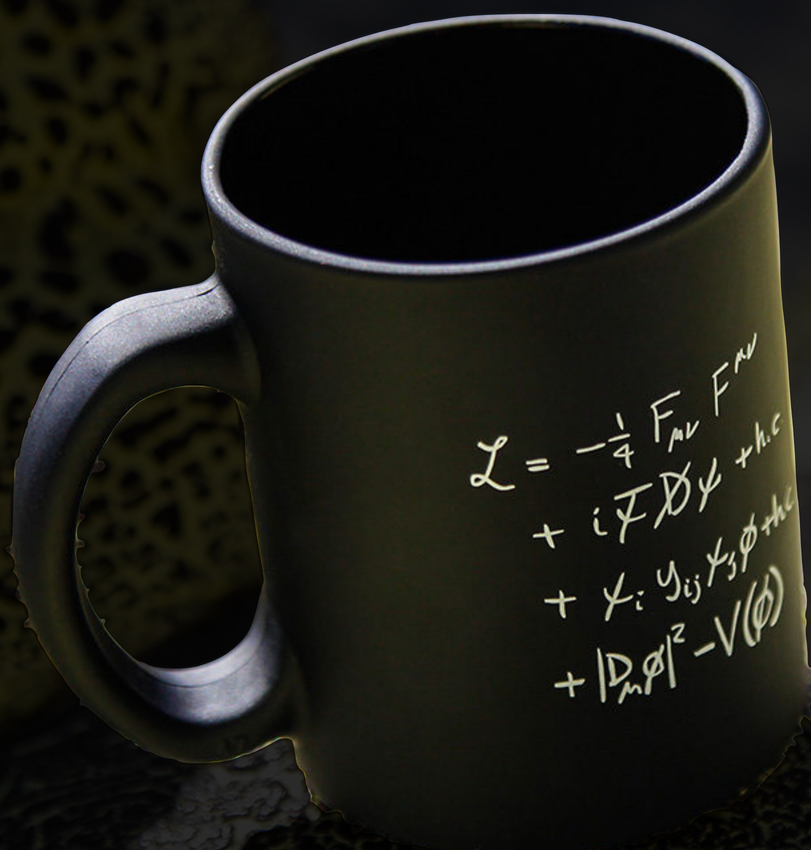
SM Lagrangian



mass terms

$m \bar{\psi} \psi$ — Fermions mass term

$m^2 V_\mu V^\mu$ — Gauge Bosons mass term

Breaks the symmetry!

SM Lagrangian

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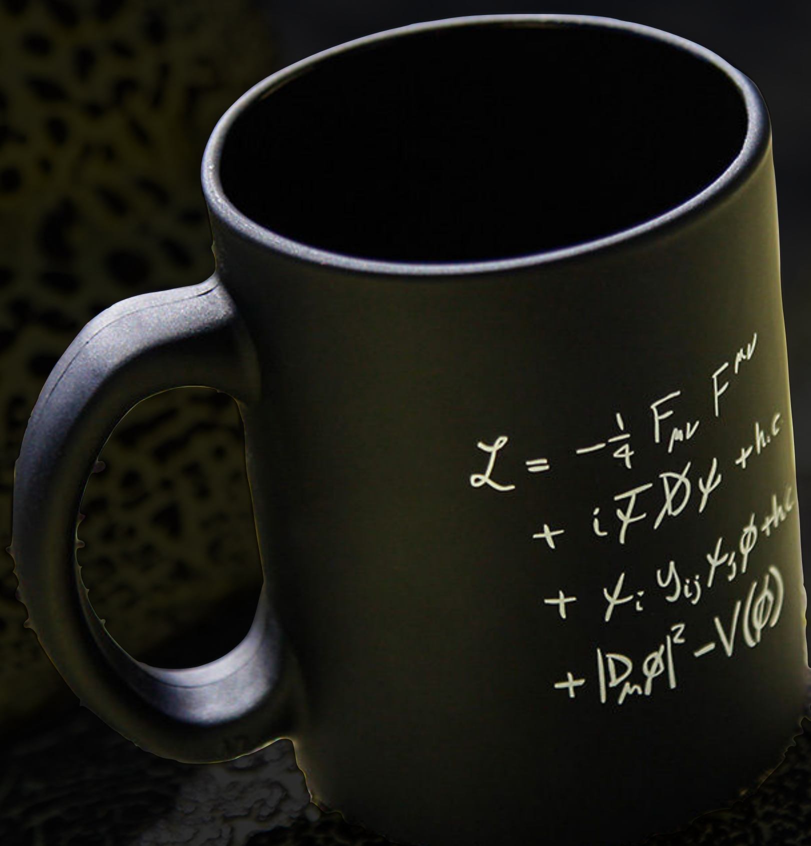
Certain transformation on ψ or V_μ according to the symmetry does not work on these mass terms

mass terms



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Breaks the symmetry!

SM Lagrangian

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mass terms

$m \bar{\psi} \psi$ — Fermions mass term

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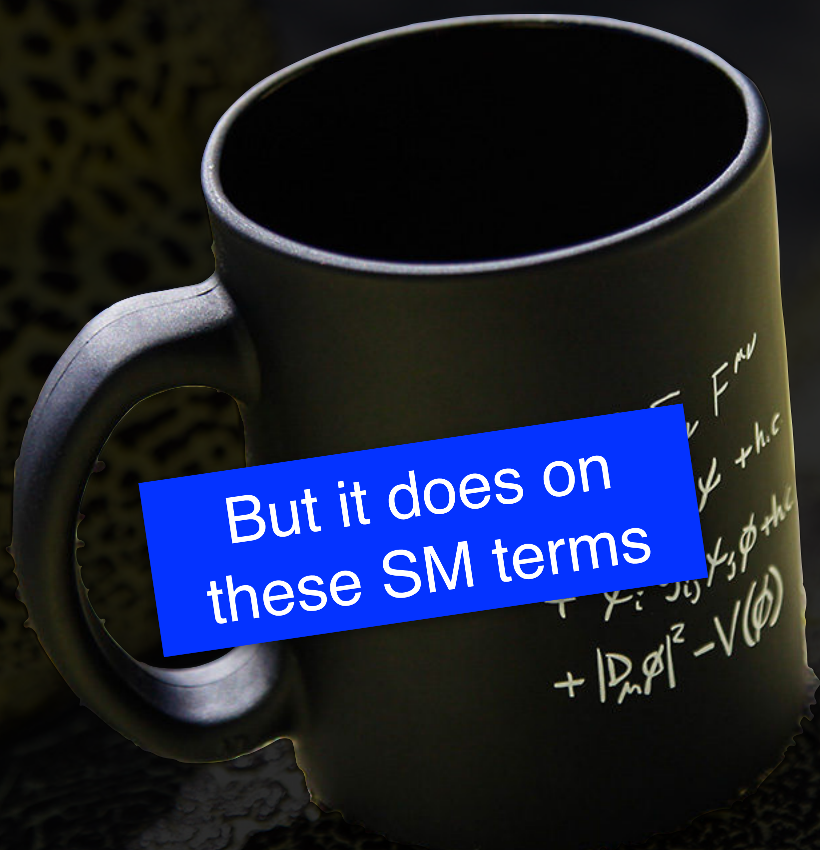

But it does on these SM terms

Breaks the symmetry!

Then… we engineer…?

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$m \bar{\psi} \psi$

breaks
symmetry

Then… we engineer…?

$m\,\bar{\psi}\,\psi \longrightarrow \phi\,\bar{\psi}\,\psi$

breaks
symmetry

Then… we engineer…?

Spin 0 particle = Higgs field!

$$m\,\bar{\psi}\,\psi \longrightarrow \phi\,\bar{\psi}\,\psi$$

breaks
symmetry

Then… we engineer…?

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Spin 0 particle = Higgs field!

↓

$m \bar{\psi} \psi \longrightarrow \phi \bar{\psi} \psi$

breaks symmetry

does not break symmetry!

Then… we engineer…?

Spin 0 particle = Higgs field!

constant value

$m\,\bar{\psi}\,\psi \longrightarrow \phi\,\bar{\psi}\,\psi$

breaks symmetry

does not break symmetry!

Then… we engineer…?

Spin 0 particle = Higgs field!

constant value

dynamical value

$m \bar{\psi} \psi \longrightarrow \phi \bar{\psi} \psi$

breaks symmetry

does not break symmetry!

SM Lagrangian

Higgs Field

ϕ

naively expect to be “quiet”
and zero everywhere

SM Lagrangian

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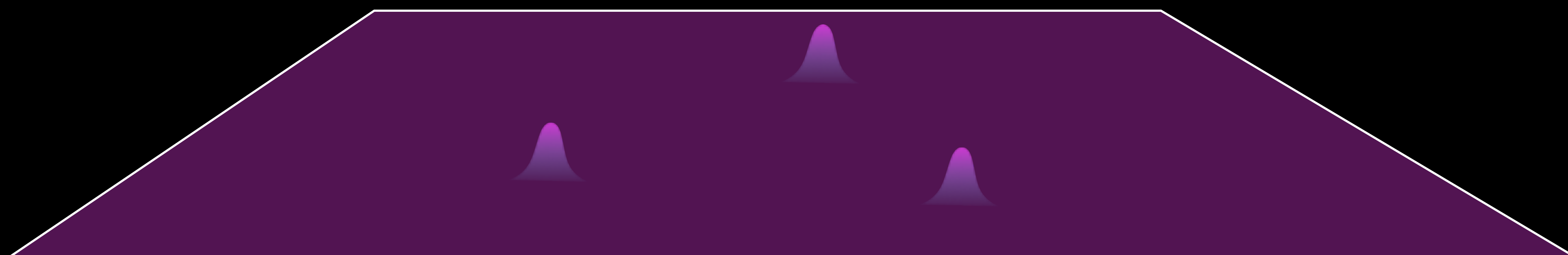
Higgs Field



ϕ

But vacuum is never quiet…

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SM Lagrangian

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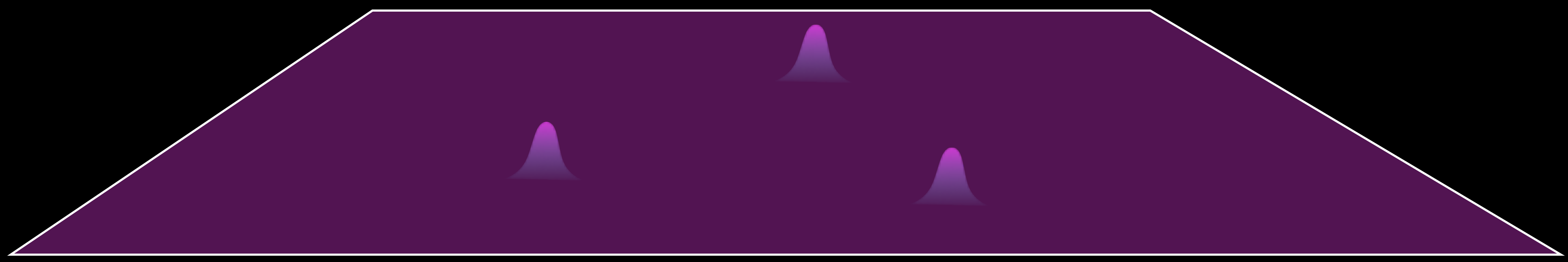
Higgs Field



ϕ

But vacuum is never quiet…

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SM Lagrangian

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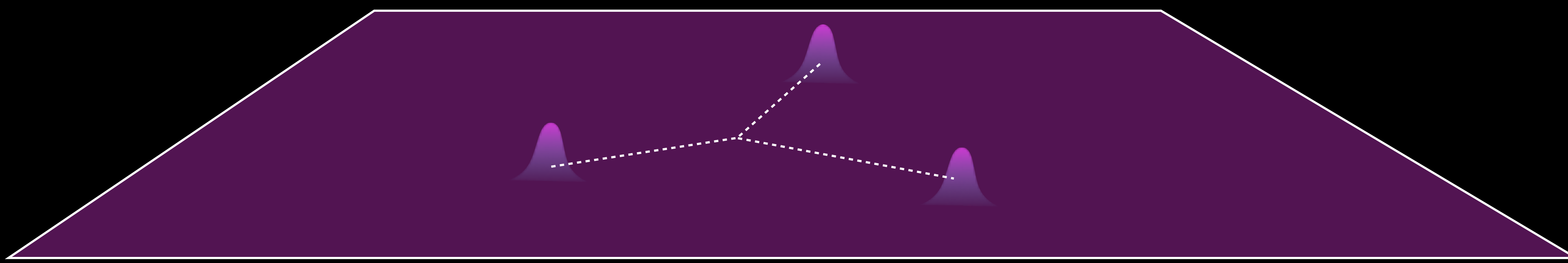
Higgs Field



ϕ

And Higgs field is unique in that it *interacts* with itself

SM Lagrangian

Higgs Field

(ϕ' + Constant)

It results in *non-zero vacuum expectation value*

SM Lagrangian

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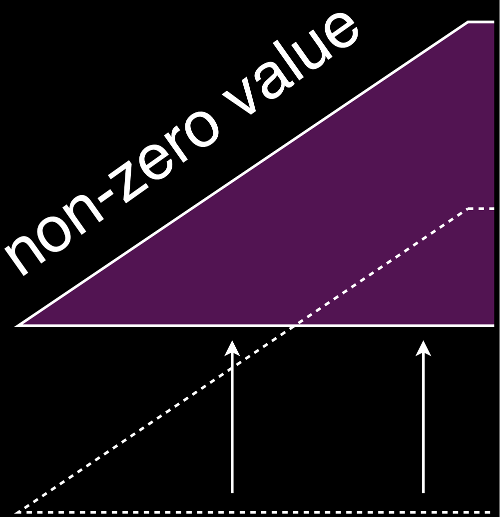
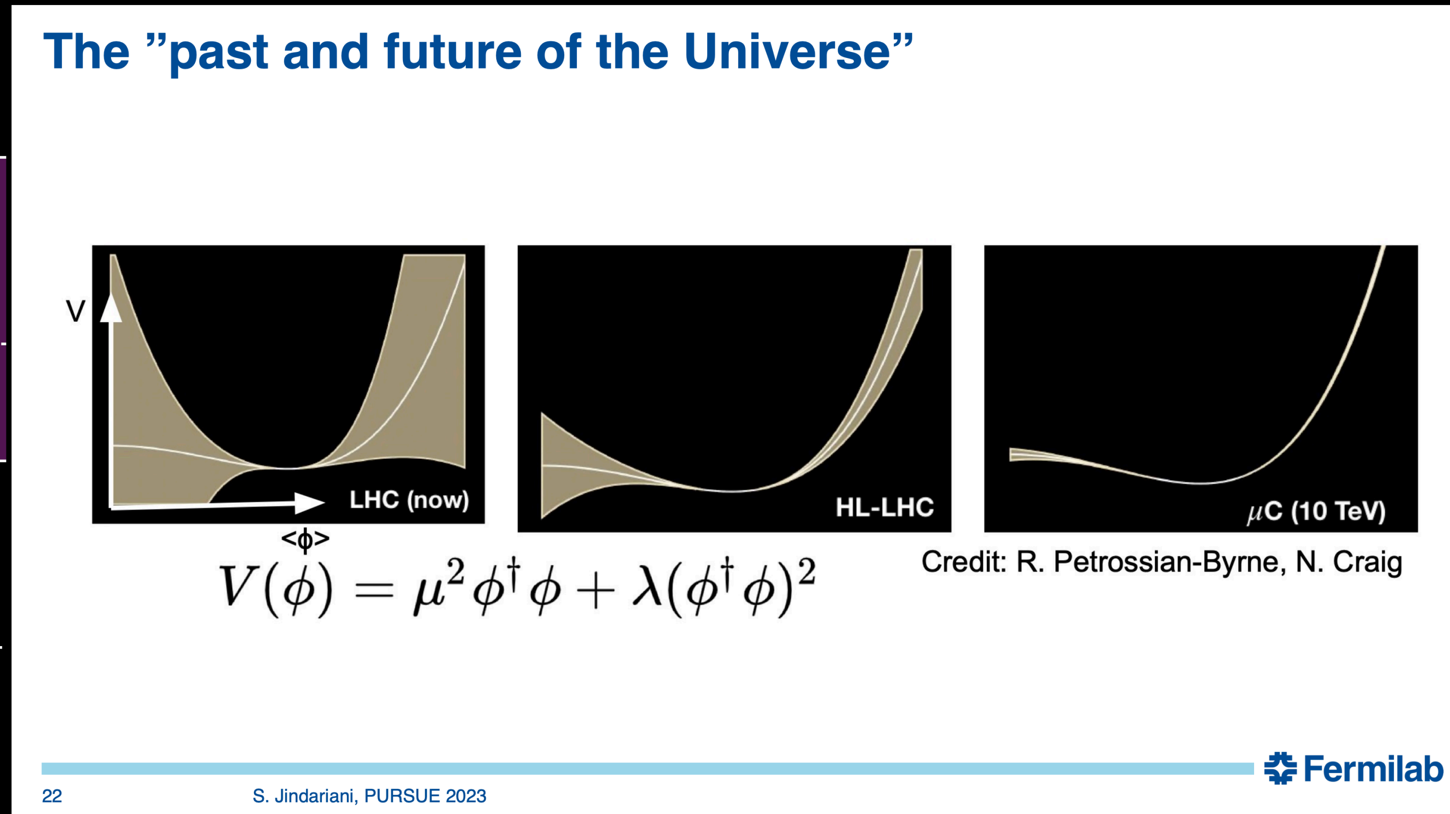
Sergo Jindariani Monday

Higgs Field





(ϕ' + Constant)

It results in *non-zero vacuum expectation value*

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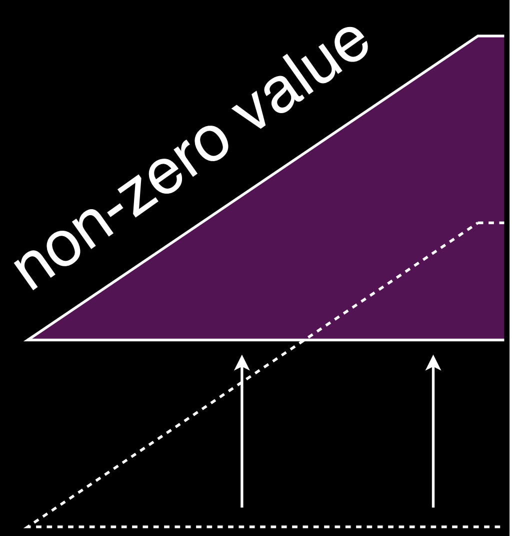
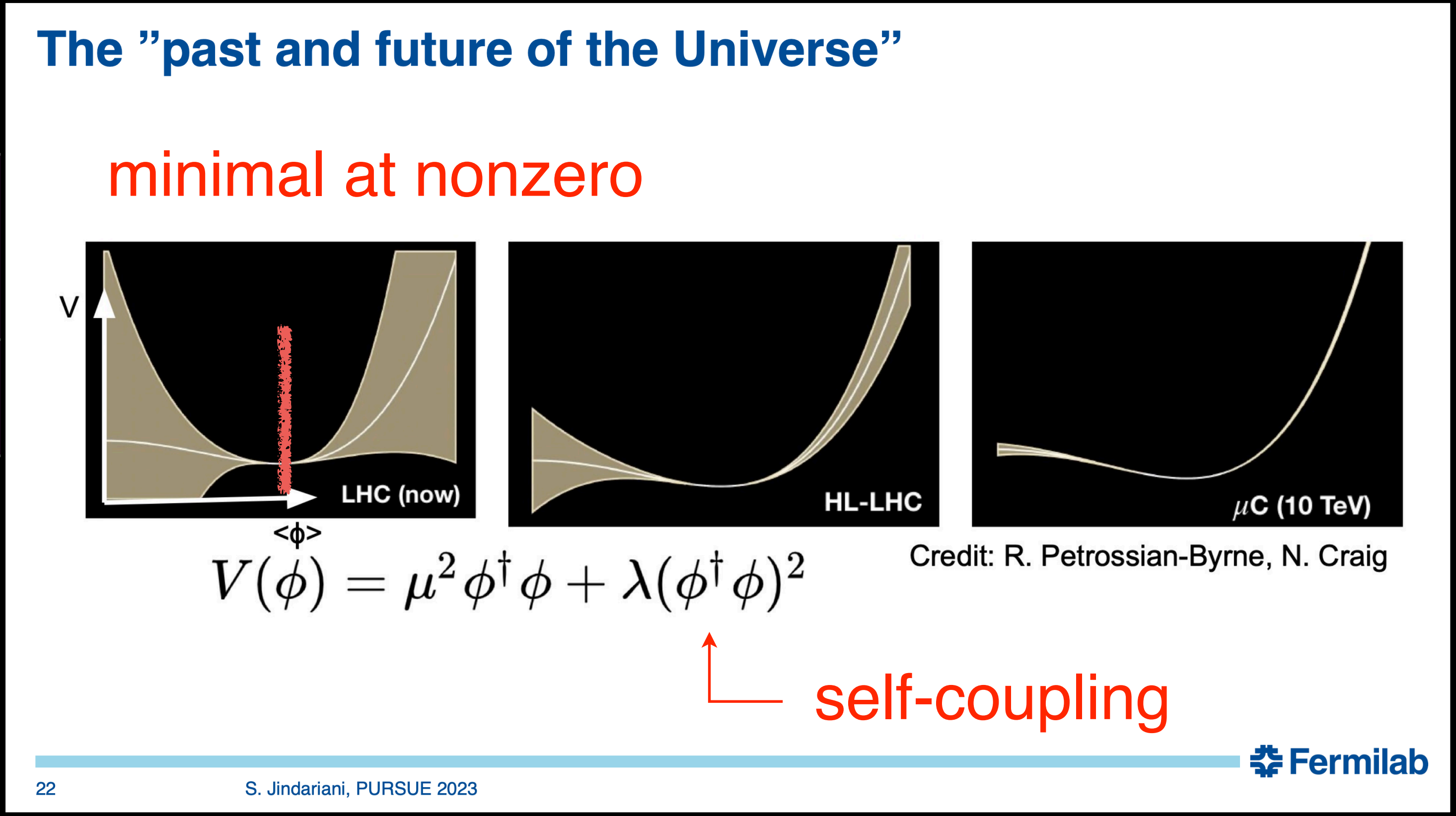
SM Lagrangian

Sergo Jindariani Monday

Higgs Field





(ϕ' + Constant)

It results in *non-zero vacuum expectation value*

SM Lagrangian

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Higgs Field

Higgs-Fermion coupling…

$(\phi' + \text{Constant})\ \bar{\psi}\ \psi$

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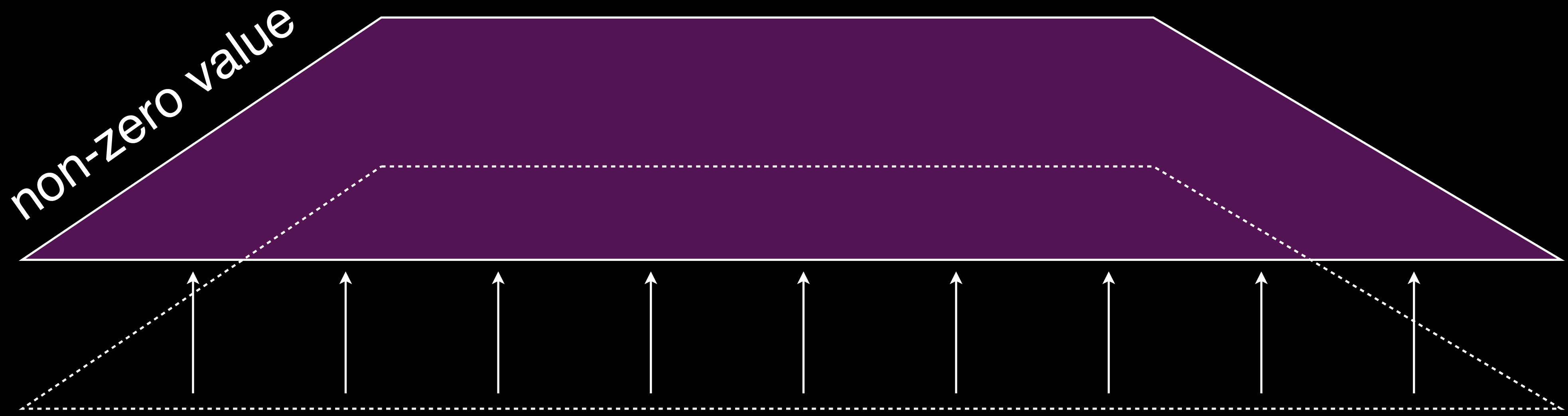
SM Lagrangian

Higgs Field



Higgs-Fermion coupling…

$(\phi' + \text{Constant})\, \bar{\psi}\, \psi$

$\phi'\, \bar{\psi}\, \psi + \text{Constant}\, \bar{\psi}\, \psi$

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

SM Lagrangian

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Higgs Field

Higgs-Fermion coupling…

$(\phi' + \text{Constant})\ \bar{\psi}\ \psi$

$\phi'\ \bar{\psi}\ \psi + \boxed{\text{Constant}\ \bar{\psi}\ \psi}$ $\quad m\ \bar{\psi}\ \psi$

mass term!

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SM Lagrangian

$\phi \; \bar{\psi} \; \psi$

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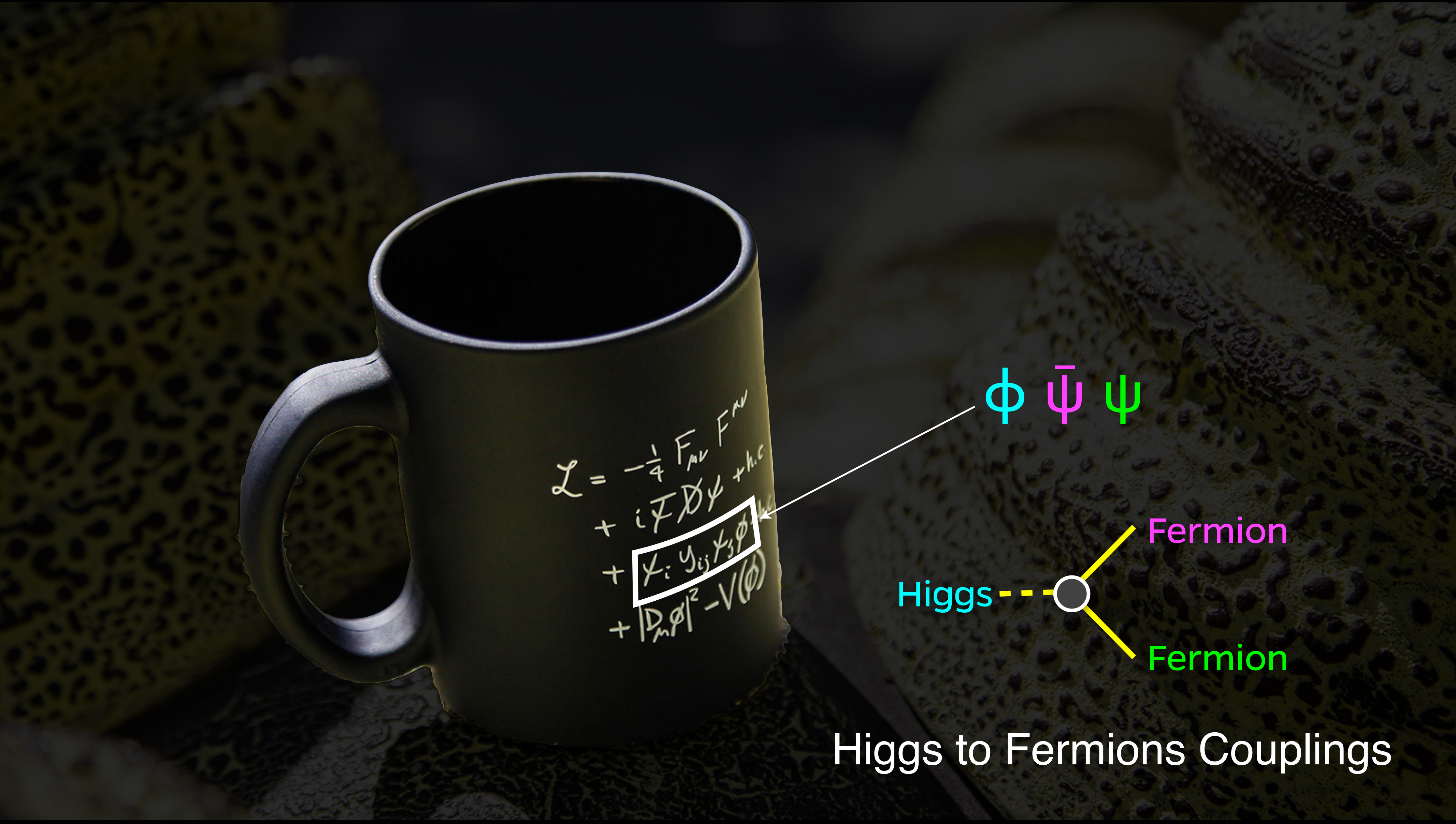
SM Lagrangian

SM Lagrangian



Standard Model

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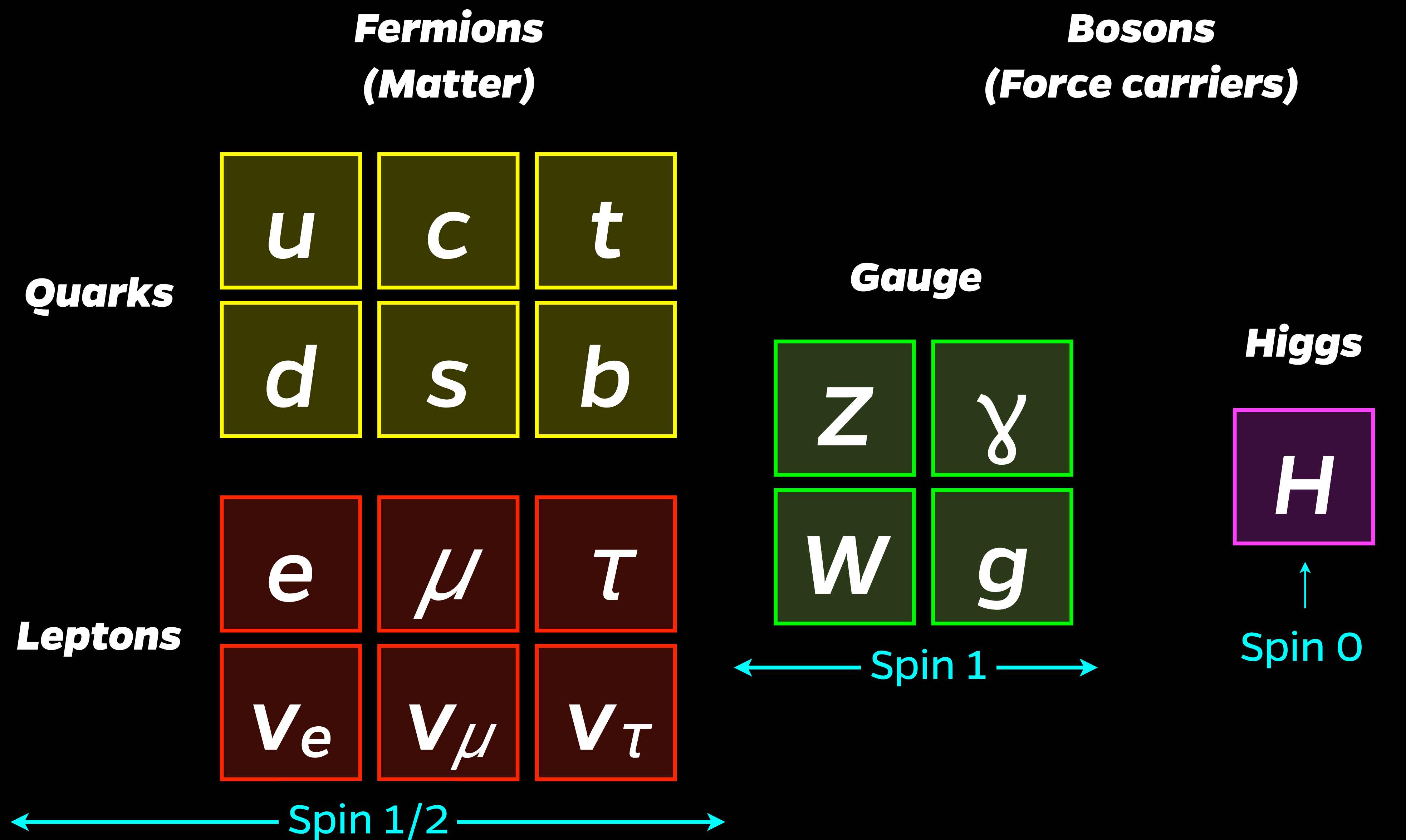
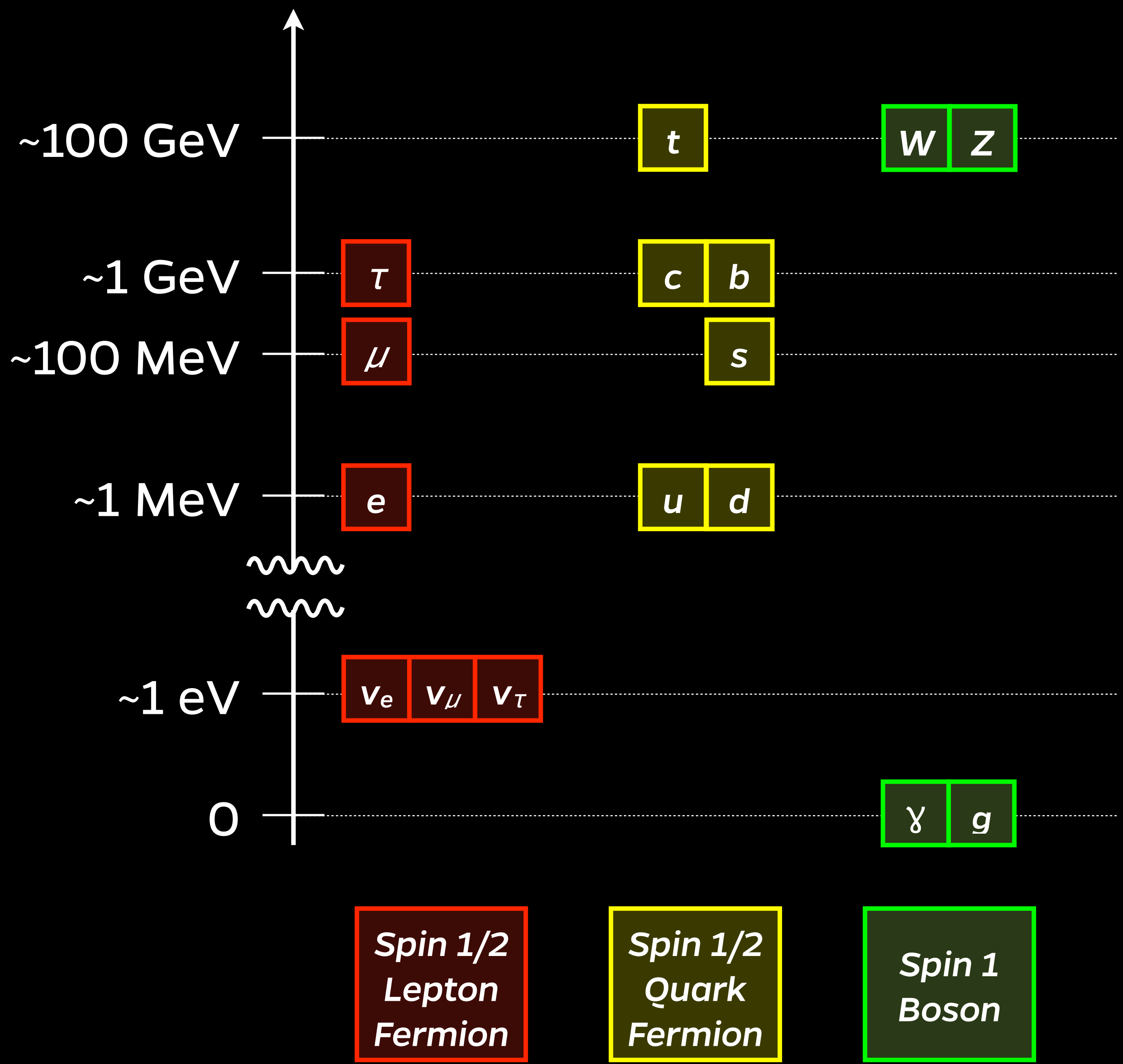
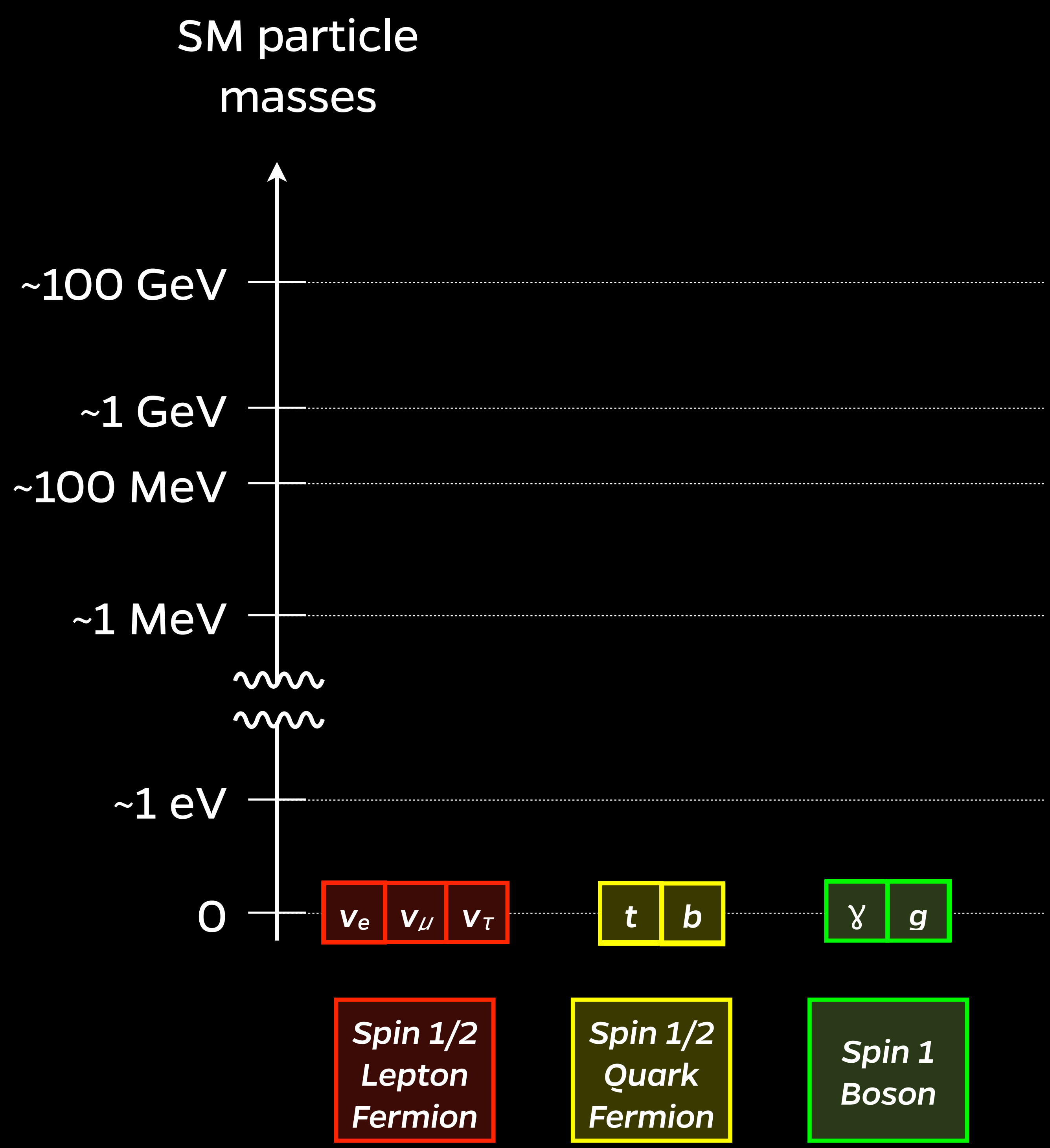


SM particle masses





SM particle masses
~100 GeV
~1 GeV
~100 MeV
~1 MeV
~1 eV
0
νe
νμ
ντ
t
b
γ
g
Spin 1/2 Lepton Fermion
Spin 1/2 Quark Fermion
Spin 1 Boson
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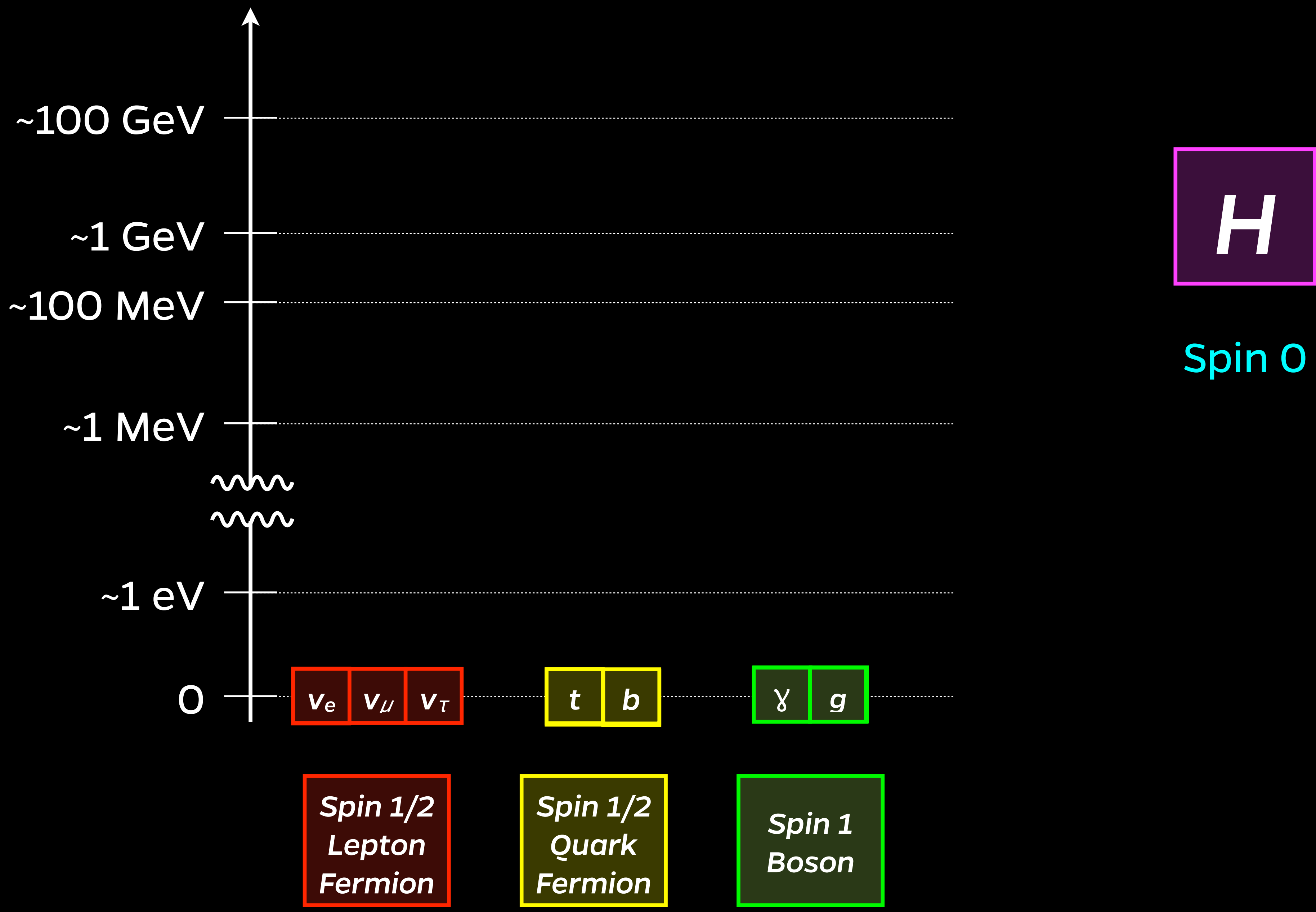
SM particle masses



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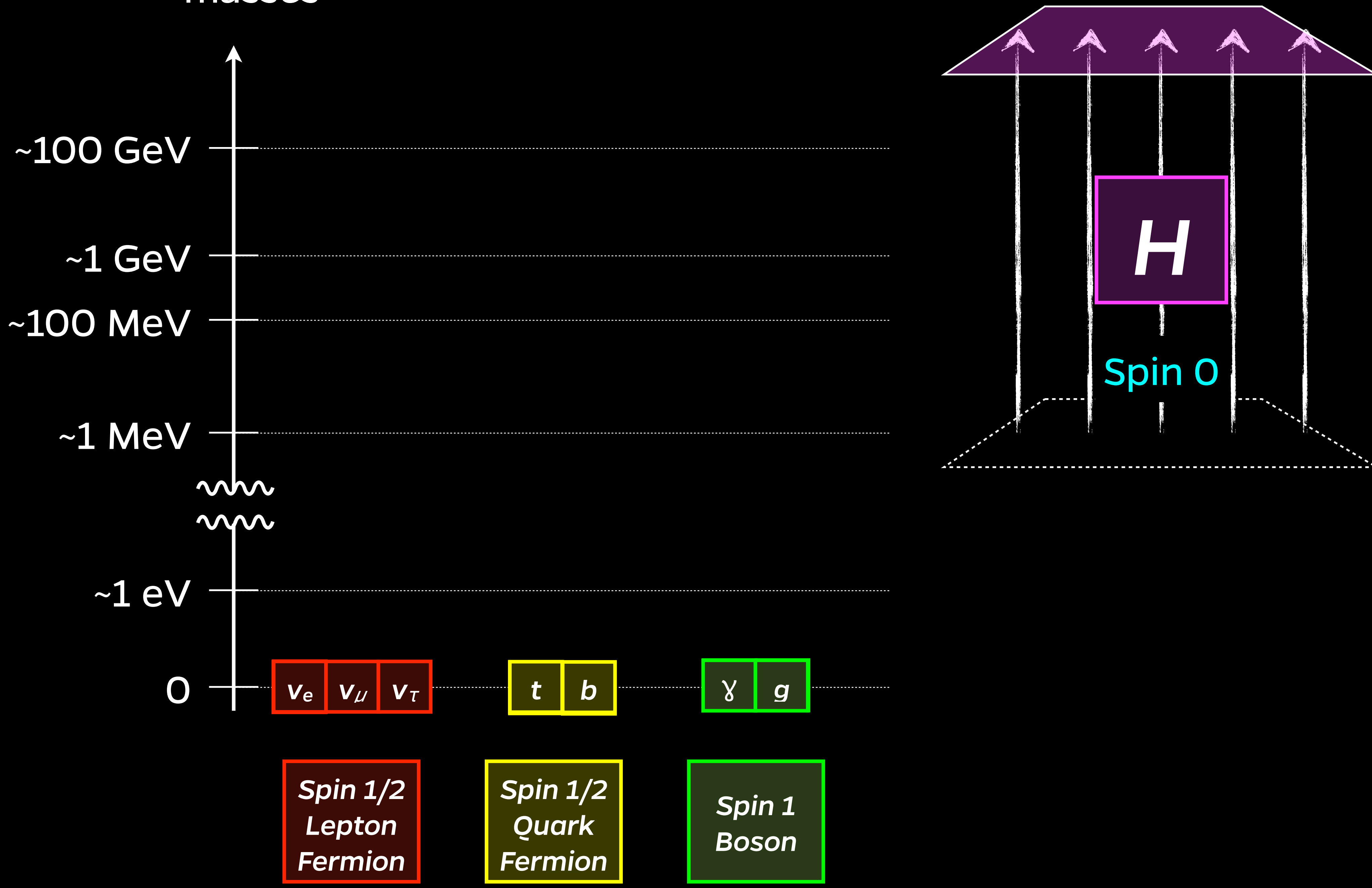
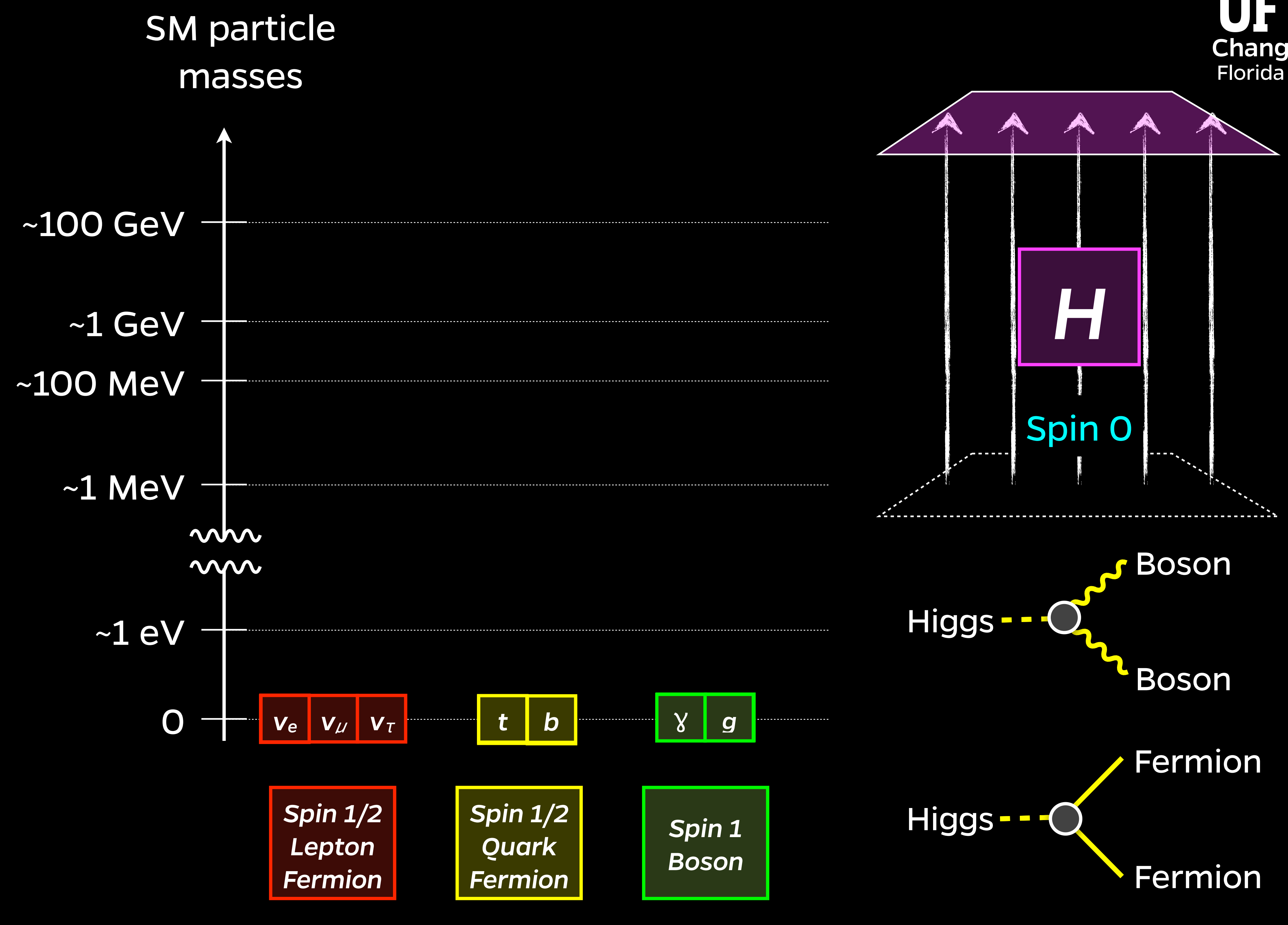
SM particle masses

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SM particle masses
~100 GeV
~1 GeV
~100 MeV
~1 MeV
~1 eV
0
ν_e
ν_μ
ν_τ
t
b
γ
g
Spin 1/2 Lepton Fermion
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H
Spin 0
Higgs
Boson
Boson
Higgs
Fermion
Fermion

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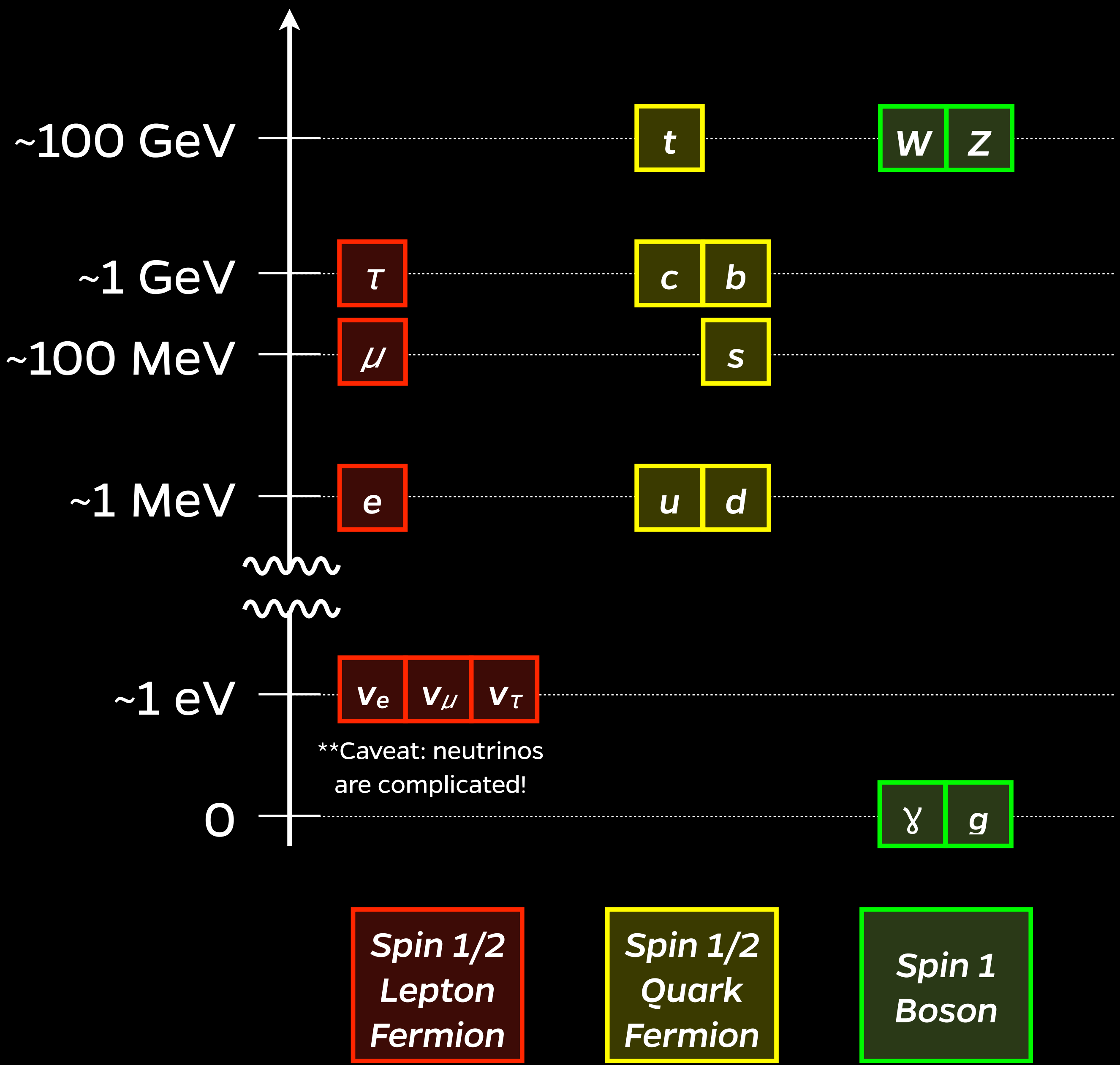
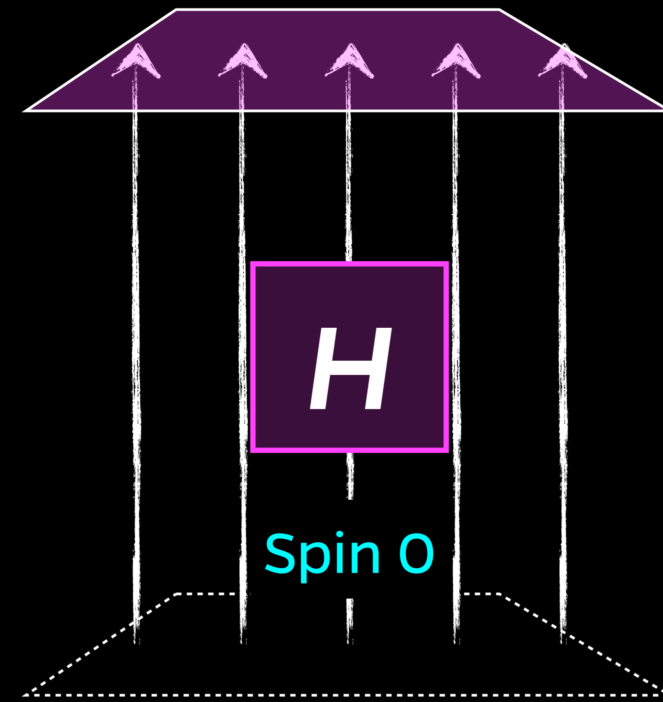
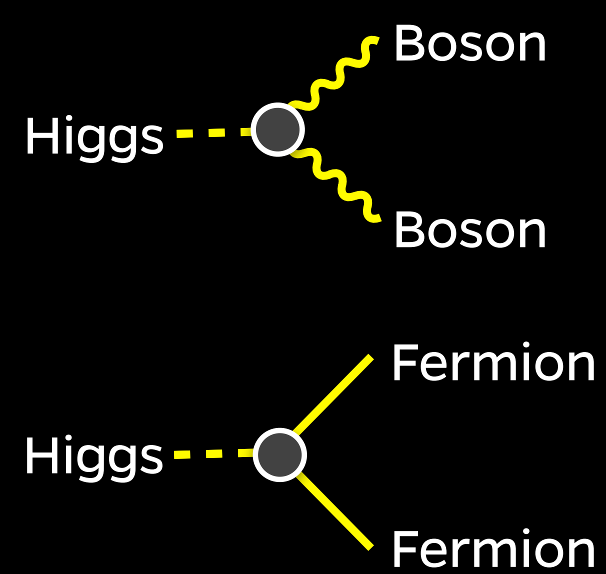
SM particle masses







Theoretically Higgs mechanism started around in 1960s

To confirm the theory we need to find Higgs field
and measure its properties

How do we find Higgs field?

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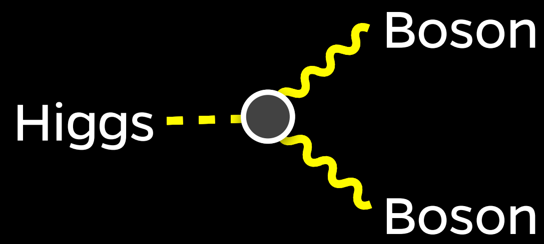

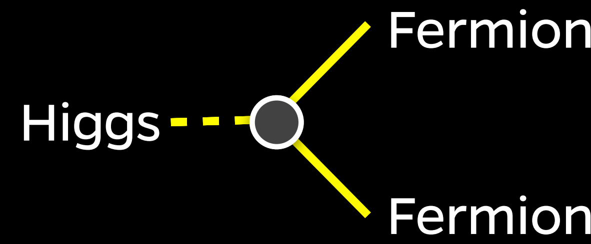

How do we find Higgs field?

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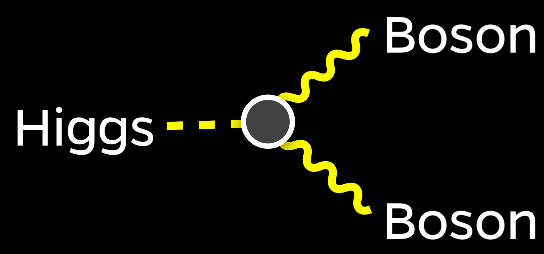
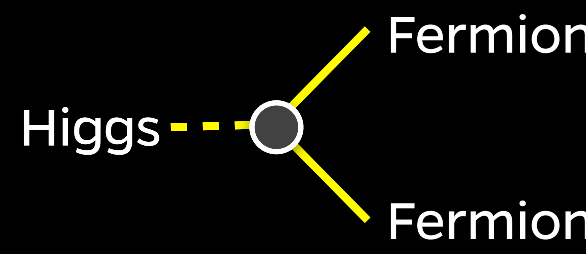
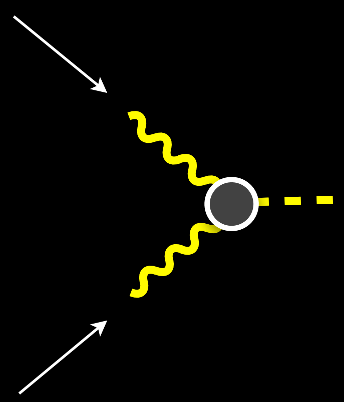
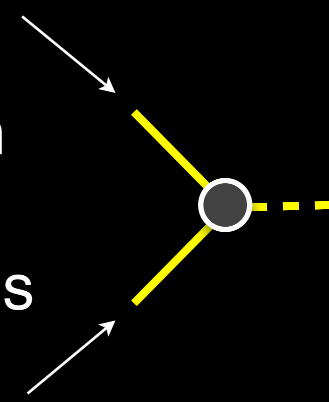




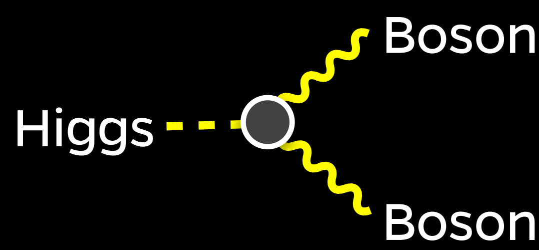
smash
SM
bosons

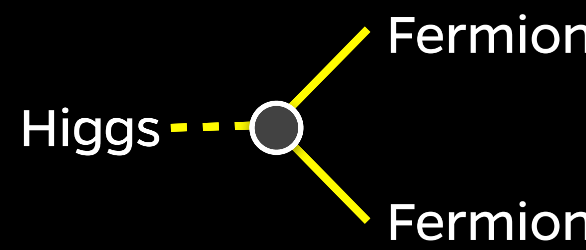


smash
SM
fermions

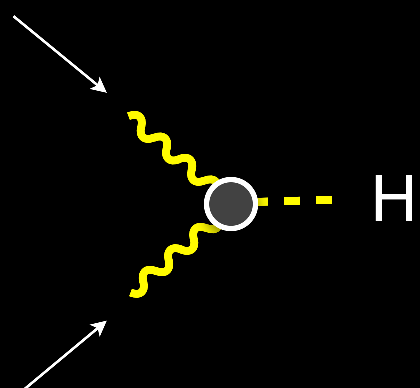


How do we find Higgs field?

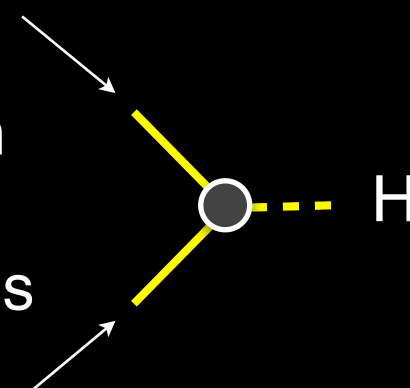




smash
SM
bosons



smash
SM
fermions



How do we find Higgs field?

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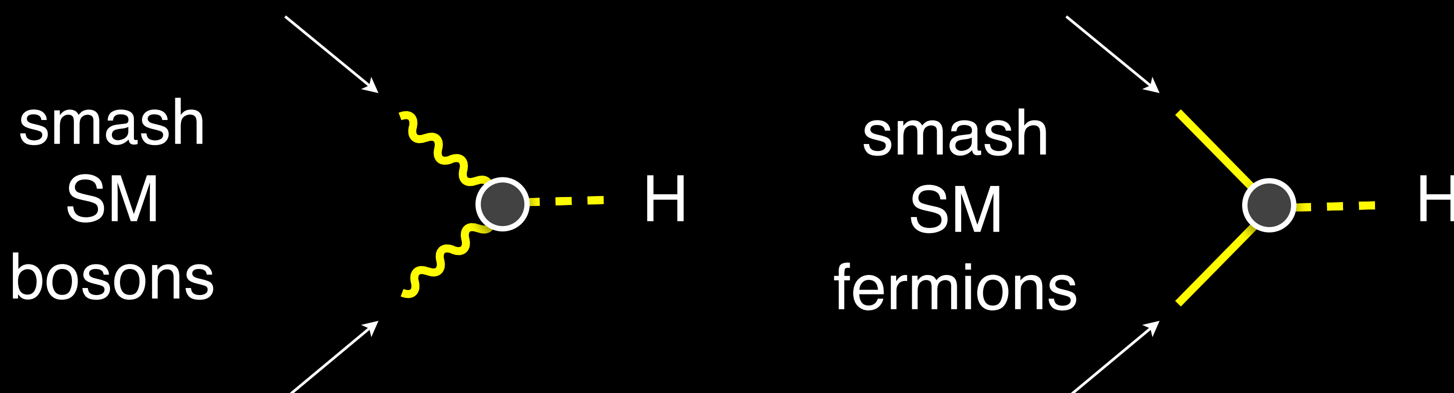
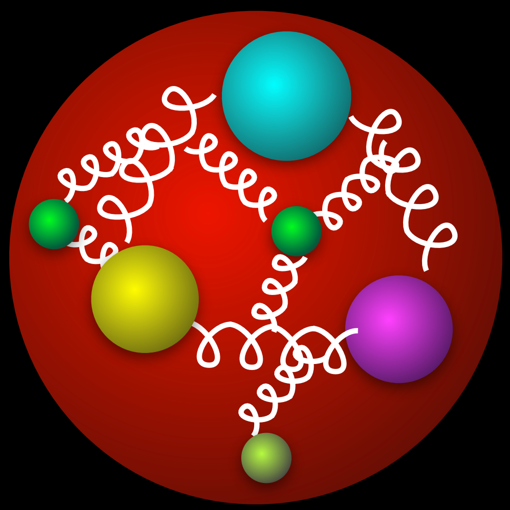


Produce Higgs boson,
an excitation of Higgs field

At the LHC

Proton



We collide protons

at the Highest energy

at the Fastest rate

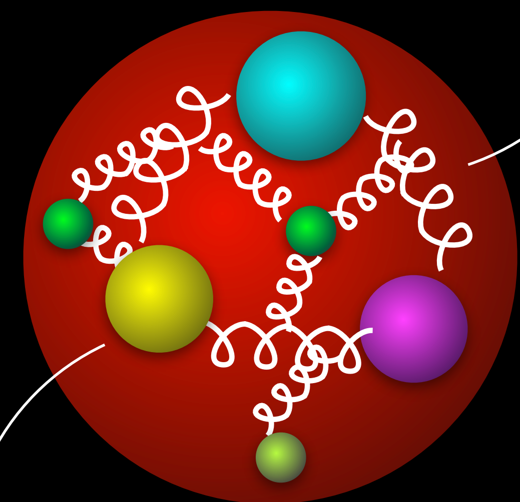
At the LHC

We collide protons

at the Highest energy

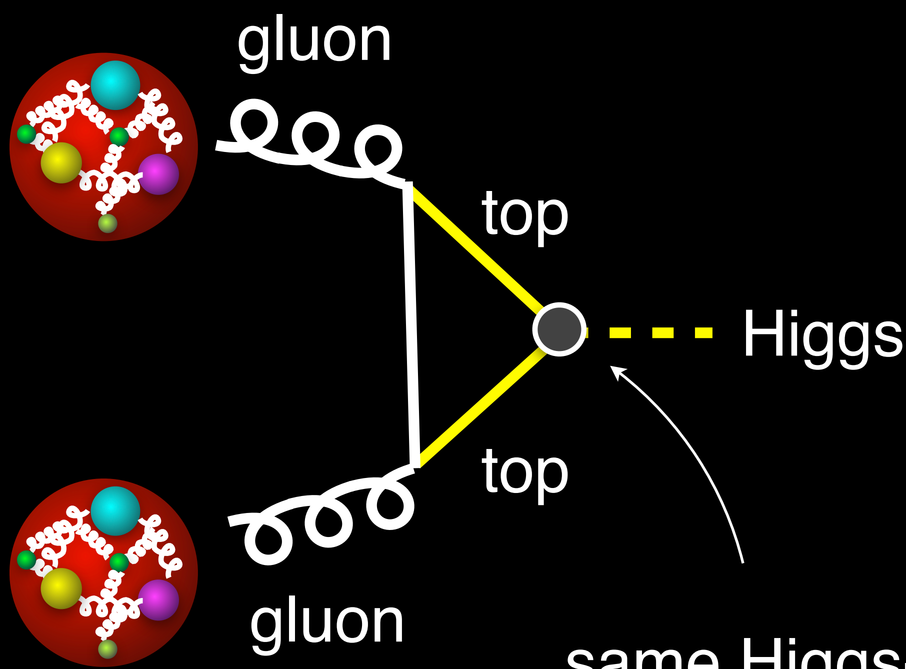
at the Fastest rate

Proton



“bag” of
quarks and gluons

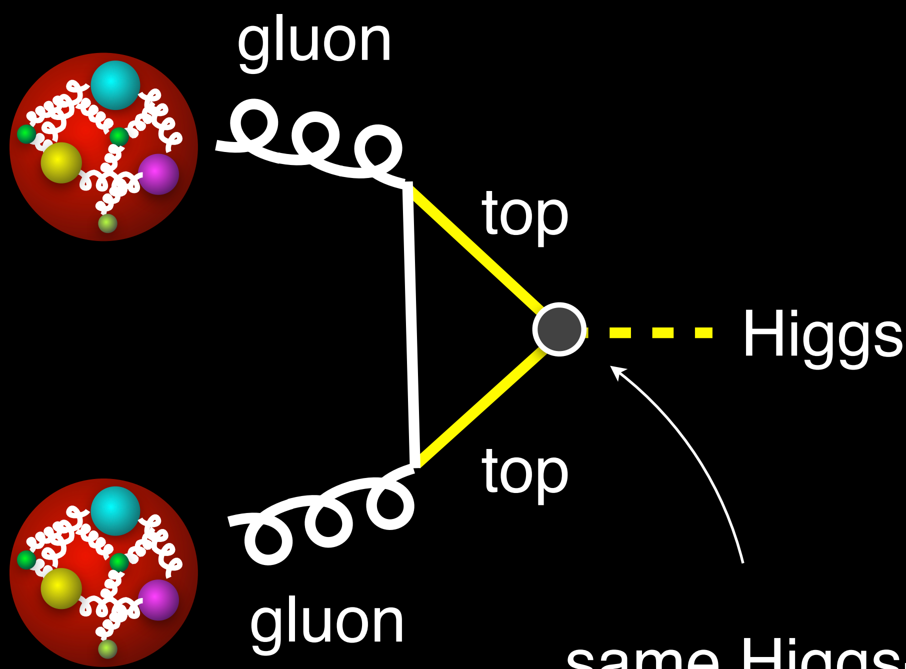
Main Higgs production modes



same Higgs-
Fermions coupling
we mentioned

Gluon Fusion
Production Mode
(ggF)

Main Higgs production modes



same Higgs-
Fermions coupling
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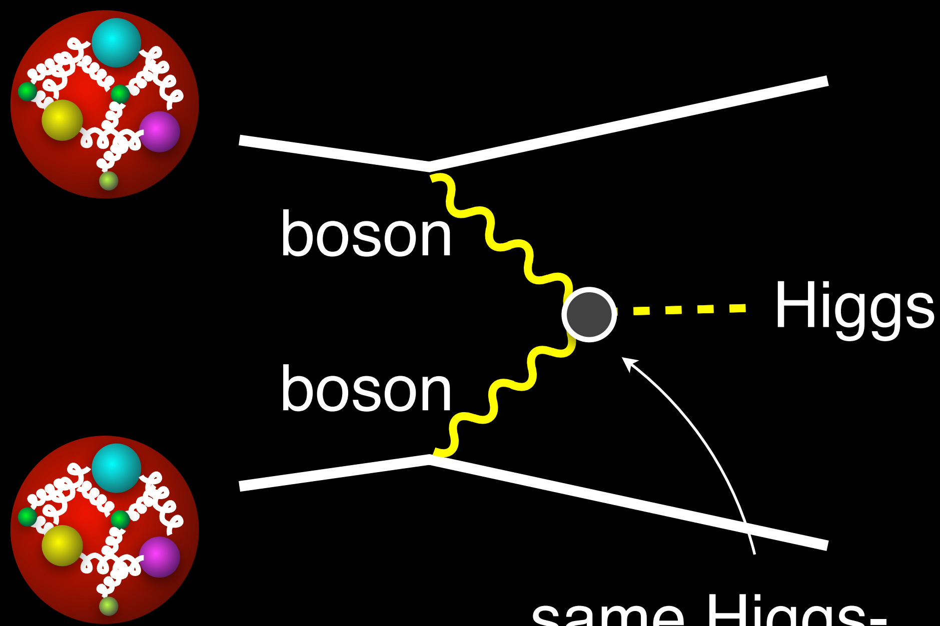
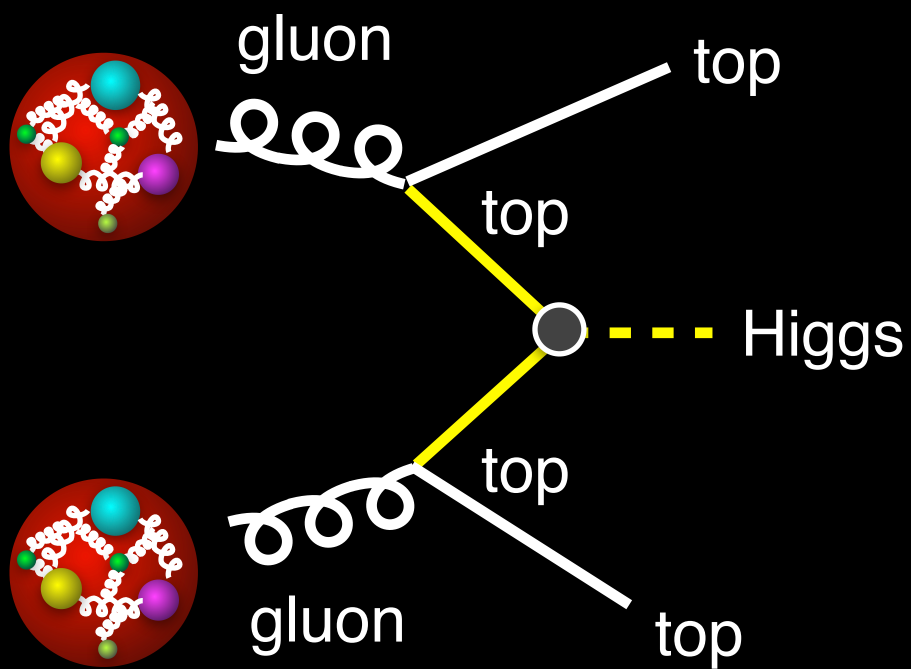
Gluon Fusion
Production Mode
(ggF)



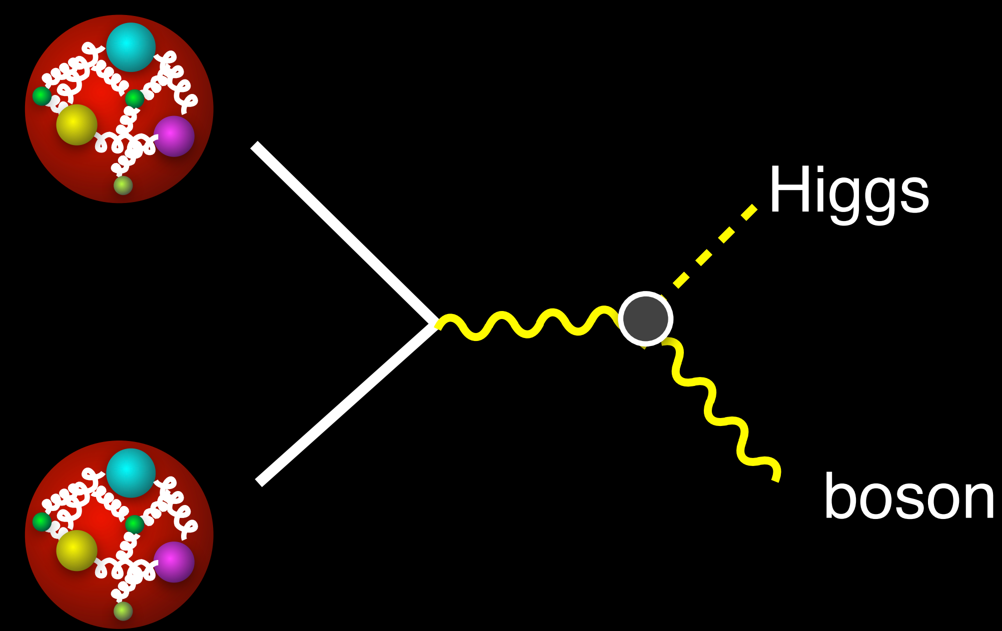
same Higgs-
bosons coupling
we mentioned

Vector Boson Fusion
Production Mode
(VBF)

Main Higgs production modes

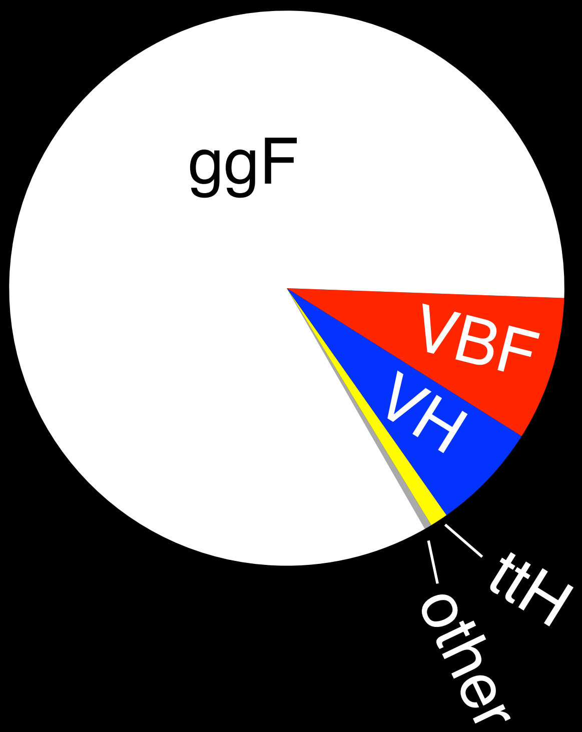


Top-associated
Production Mode
(ttH)



Vector boson-associated
Production Mode
(VH)

Production Fractions



❶ Gluon Fusion (ggF)

❷ Vector Boson Fusion (VBF)

❸ Vector Boson Associated Production (VH)

❹ Top quark Associated Production (ttH)

Production Fractions

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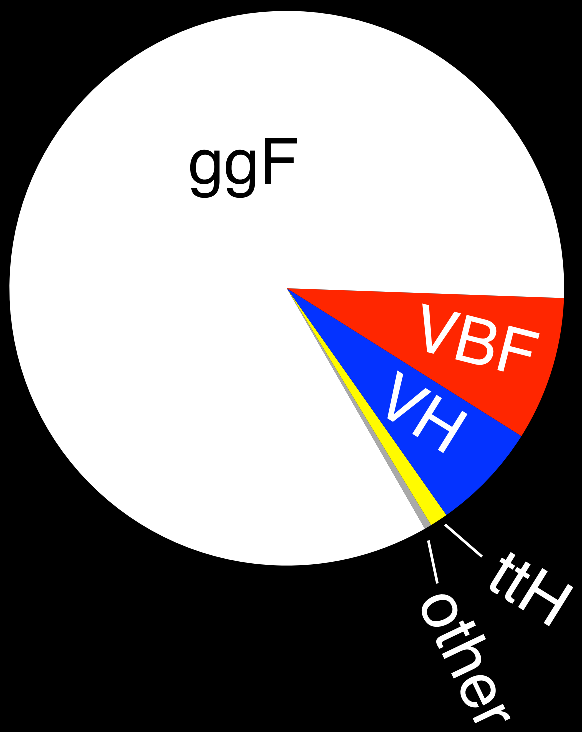
once every 4 billion proton collisions



❶ Gluon Fusion (ggF)

❷ Vector Boson Fusion (VBF)

❸ Vector Boson Associated Production (VH)

❹ Top quark Associated Production (ttH)

Production Fractions

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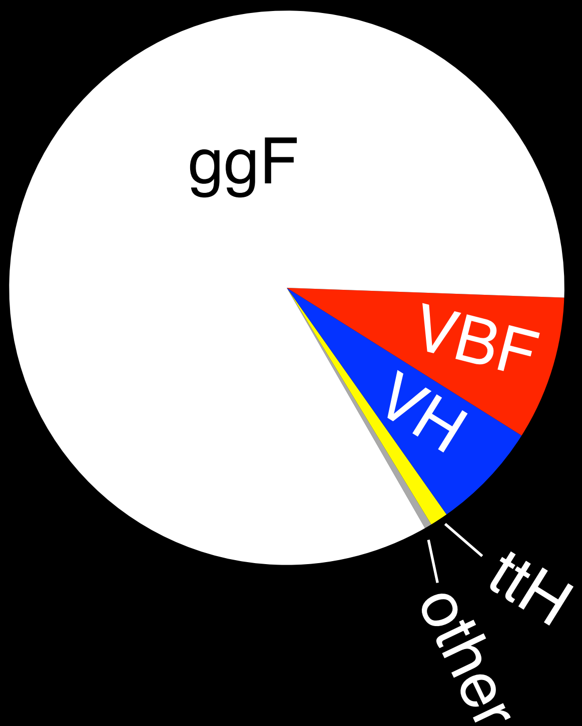


once every 4 billion proton collisions

❶ Gluon Fusion (ggF)

10x smaller

❷ Vector Boson Fusion (VBF)

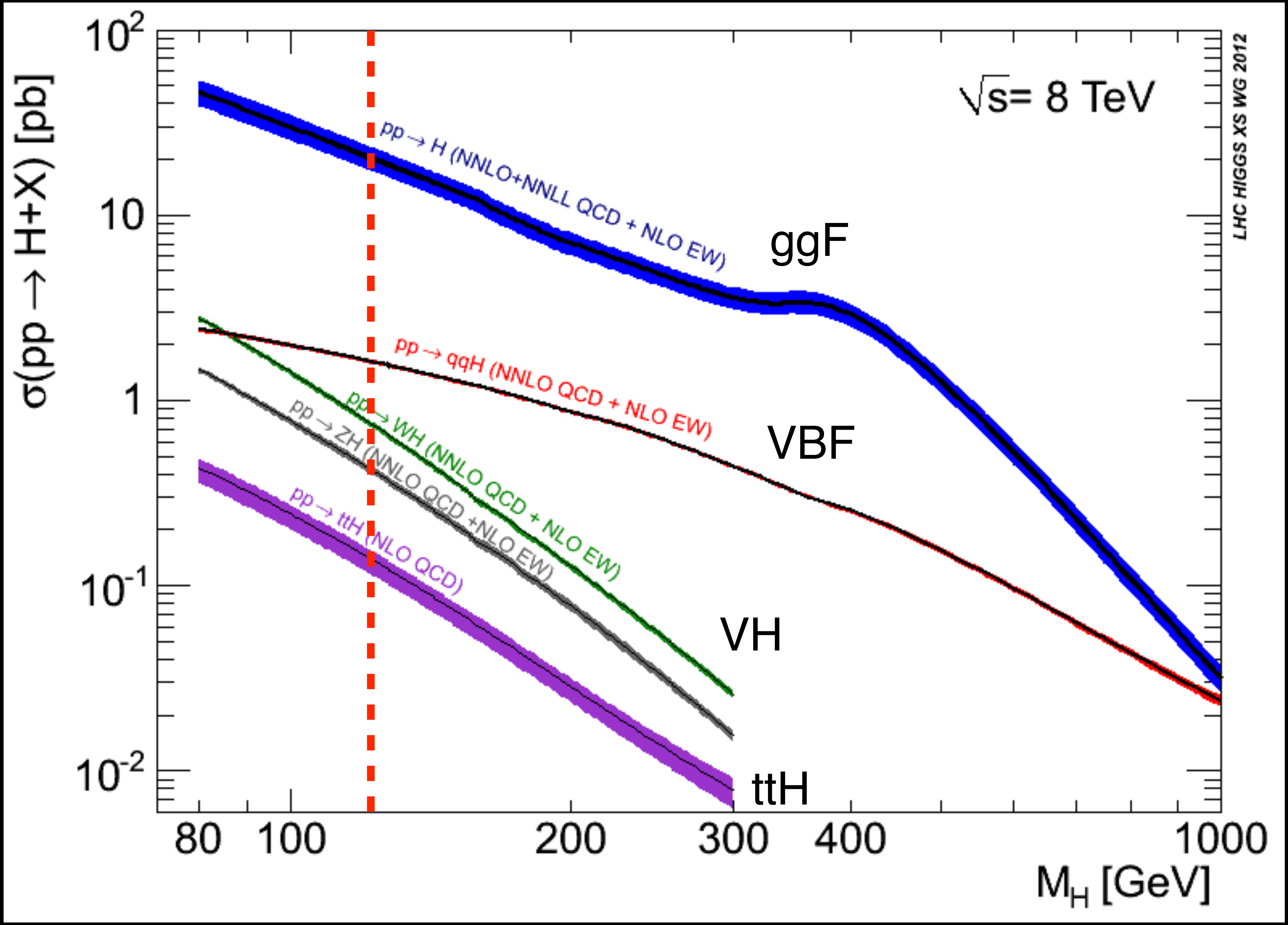
1.5x smaller

❸ Vector Boson Associated Production (VH)

10x smaller

❹ Top quark Associated Production (ttH)

Production as a function of mass



Production as a function of mass

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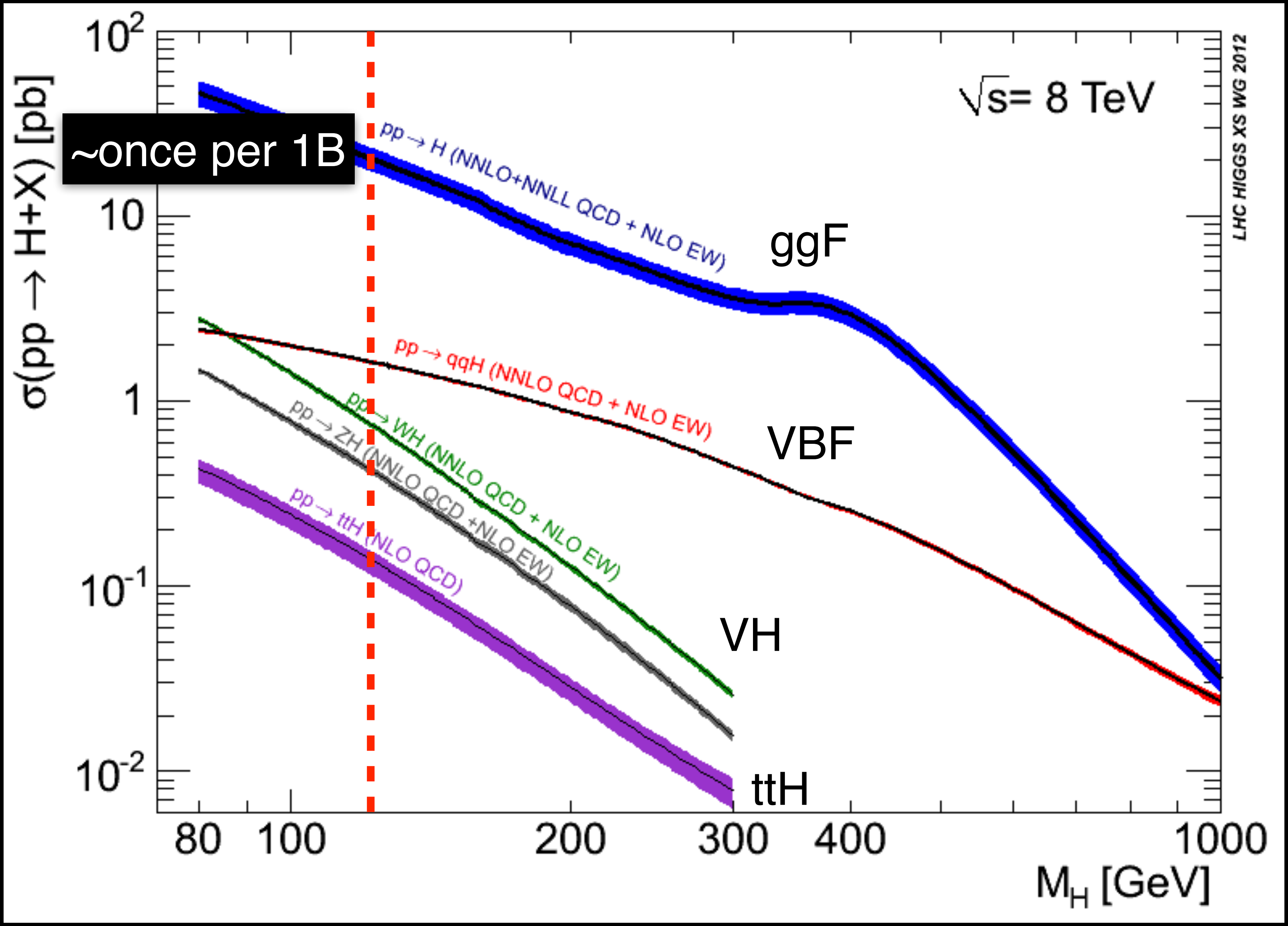

Production as a function of mass

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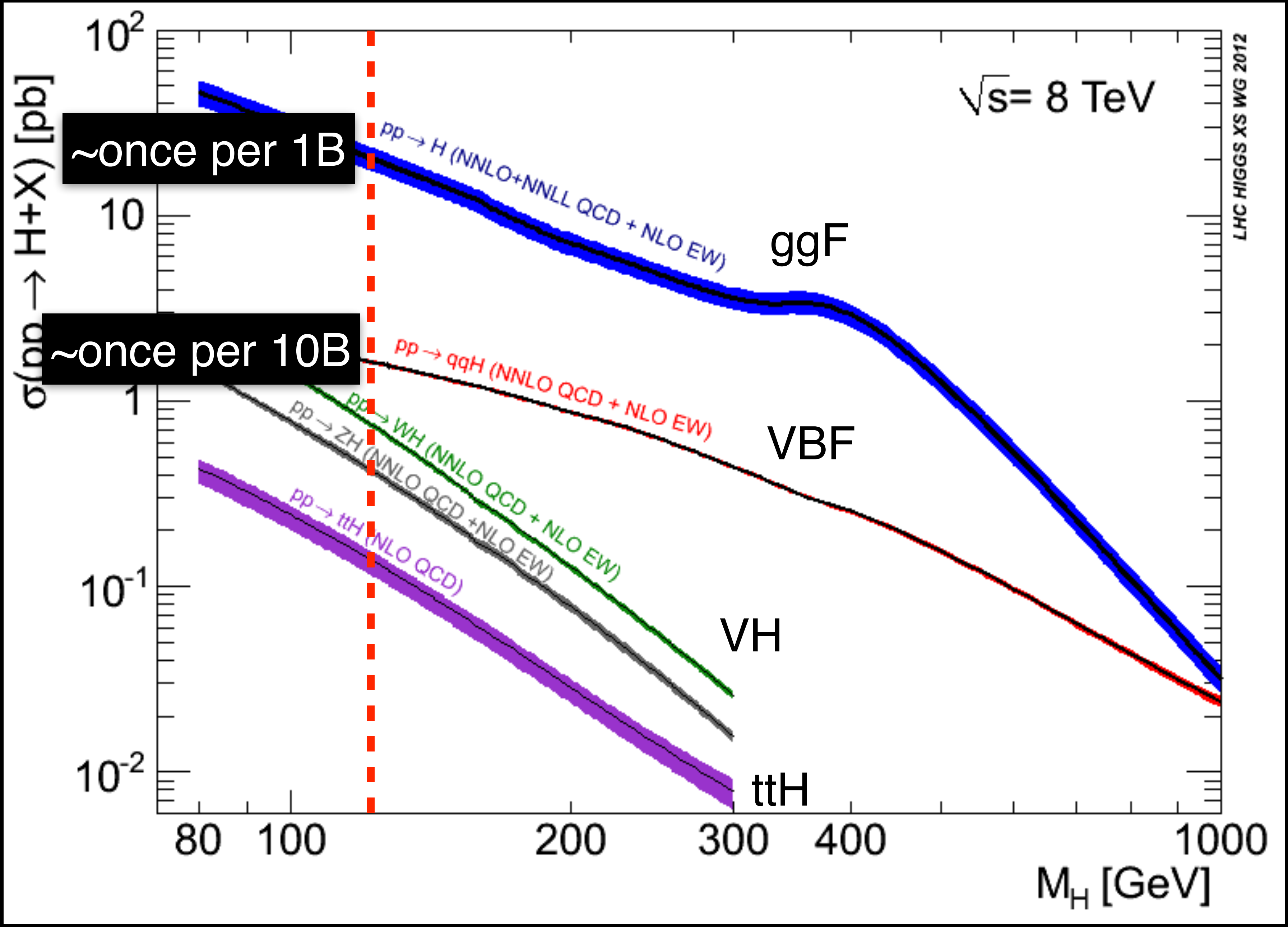
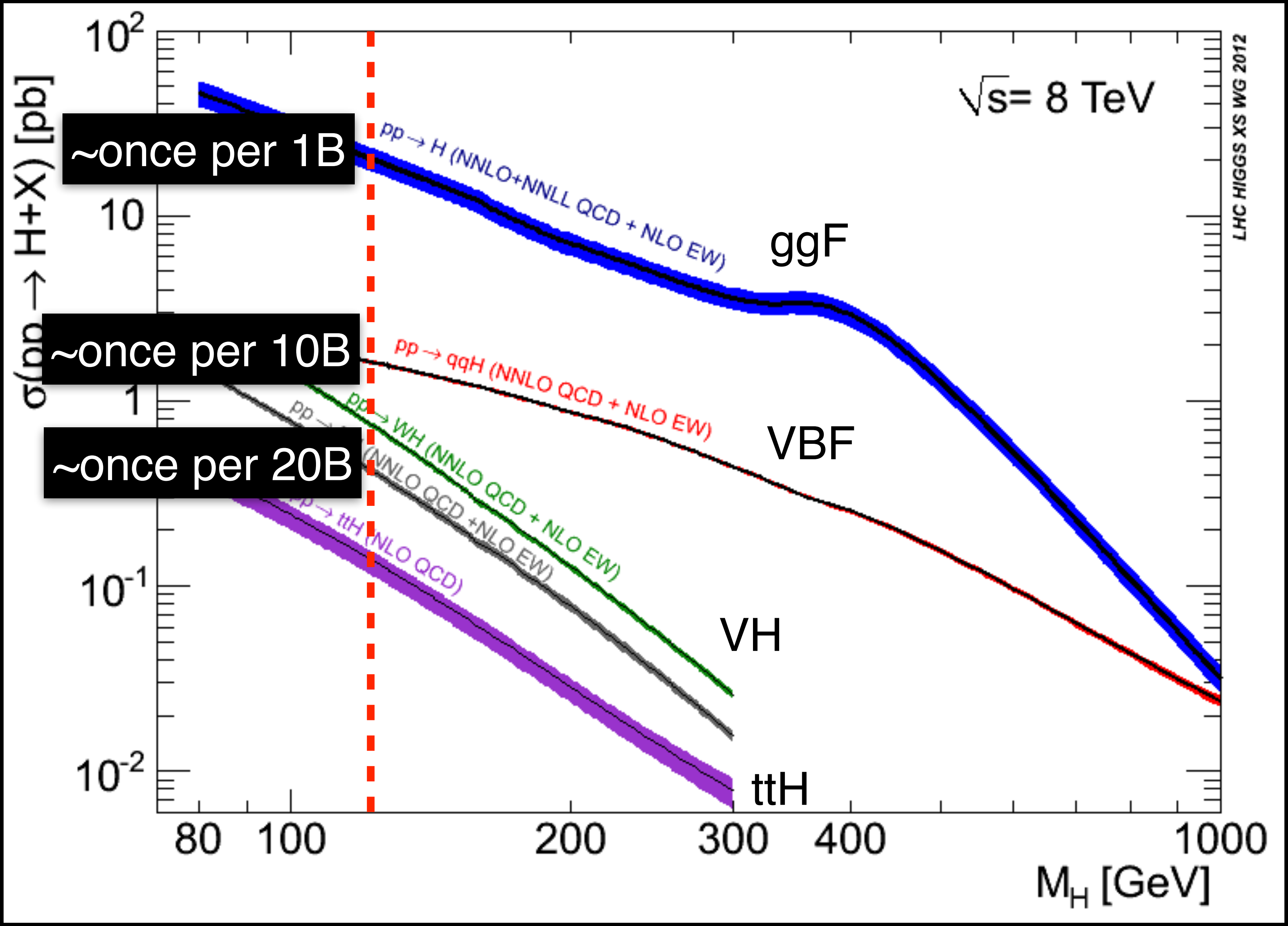


Production as a function of mass



Production as a function of mass

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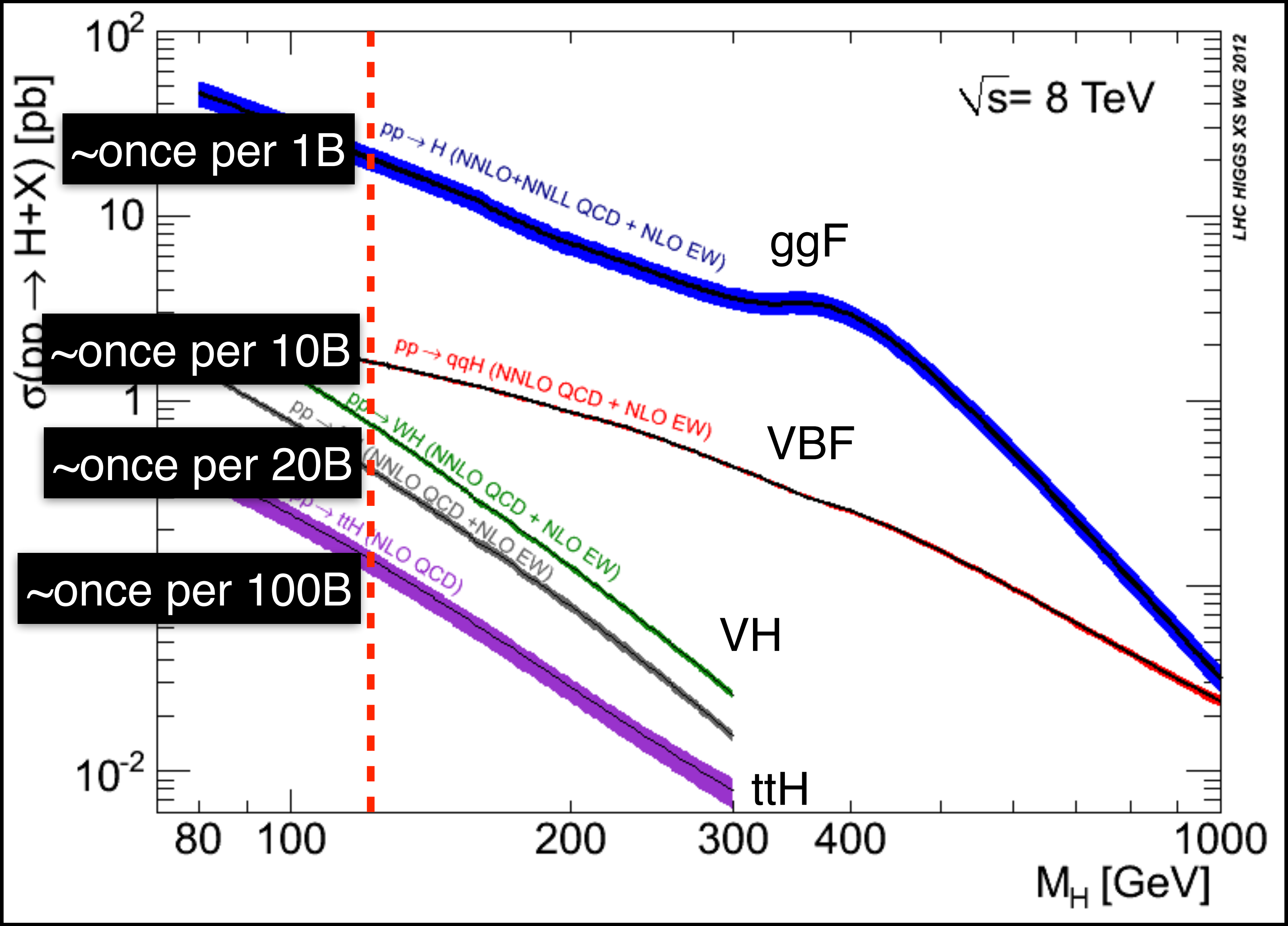

Rule of thumb numbers

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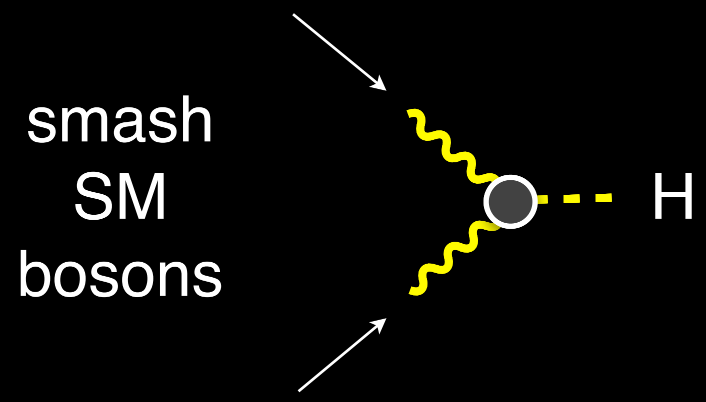
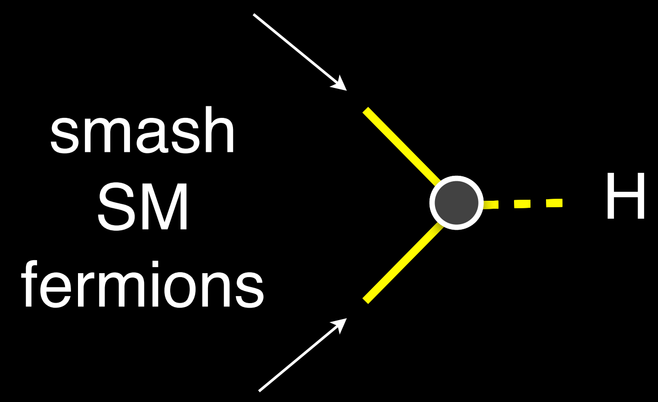
In Run 1, ~20000 Higgs events per 1 fb^{-1} at 8 TeV
pp collision of ~20 fb^{-1} → ~0.4 M Higgs events

In Run 2/3, ~50000 Higgs events per 1 fb^{-1} at 13/13.6 TeV
pp collision of ~265 fb^{-1} → 13 M Higgs events

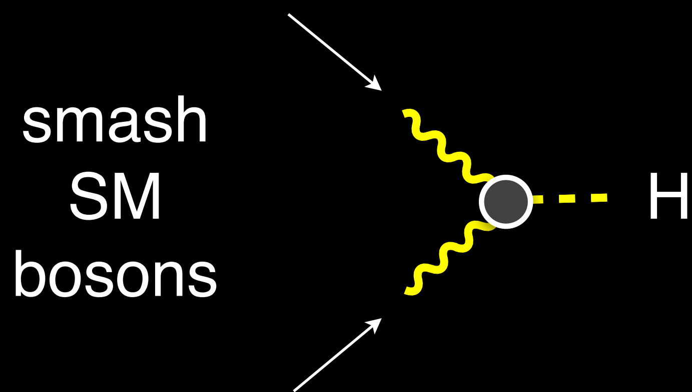
Once Higgs is produced…

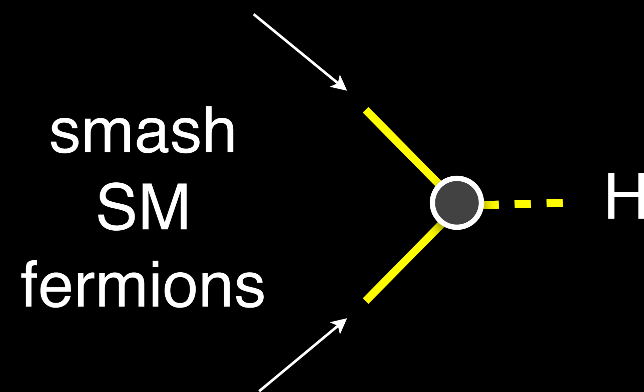




Higgs boson couples to many particles

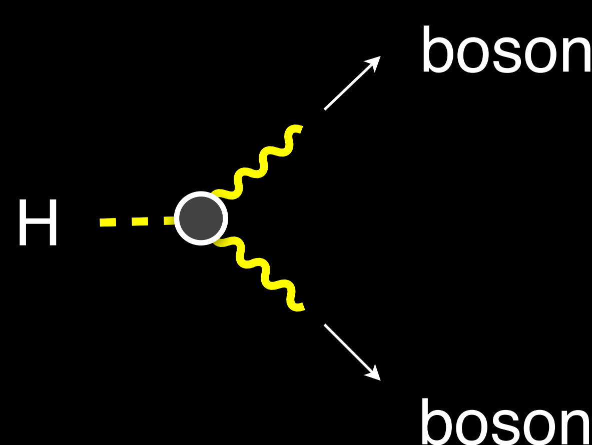
Once Higgs is produced…

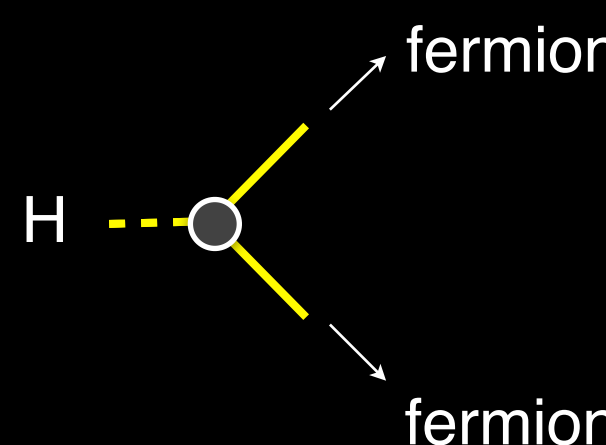




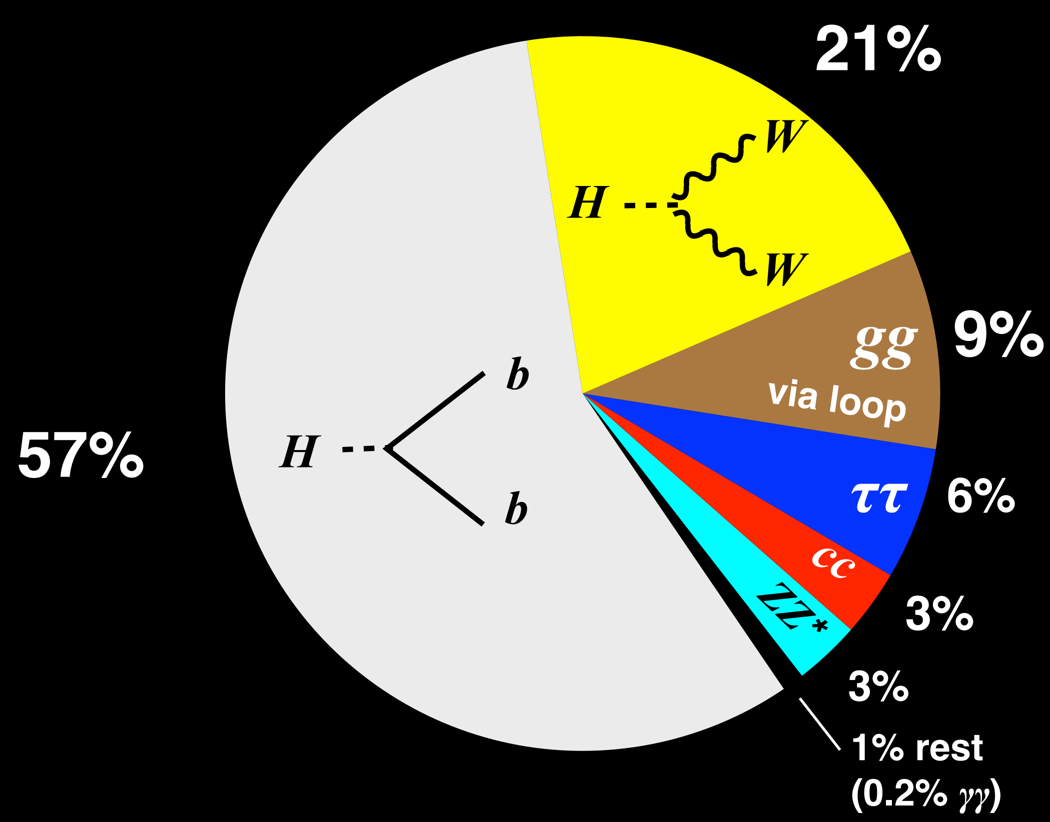
Higgs boson couples to many particles

⇒ Higgs will decay into pair of particles!





Branching Fractions



Branching Fractions

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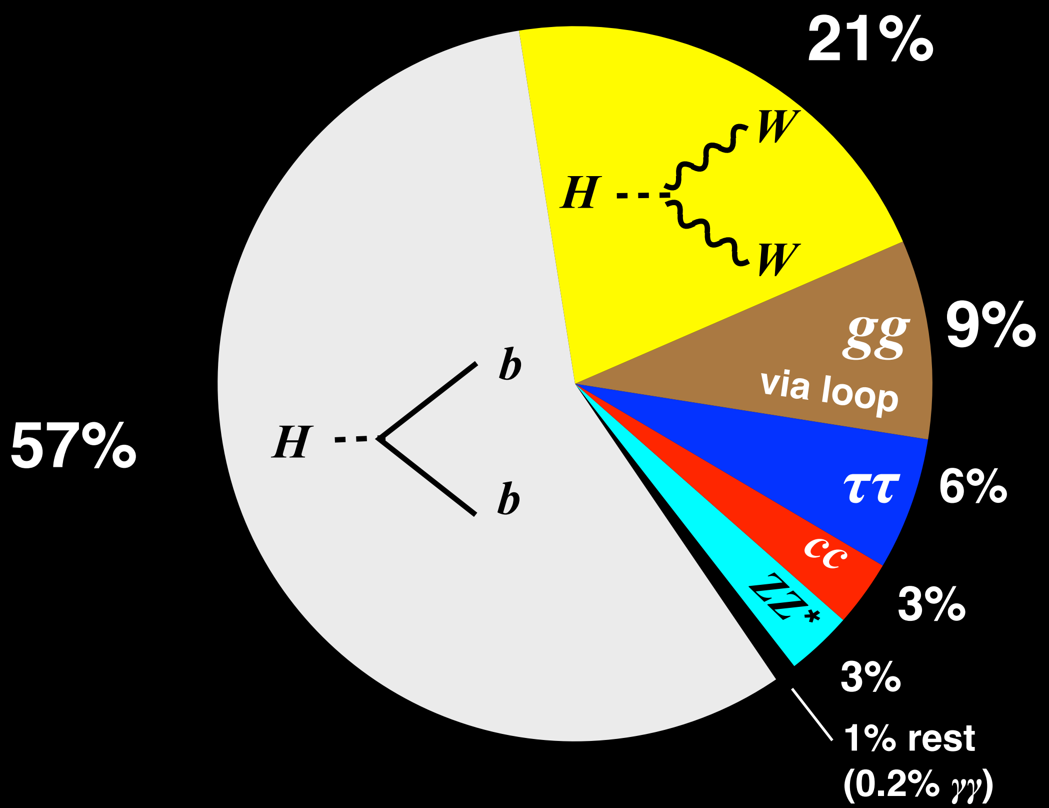
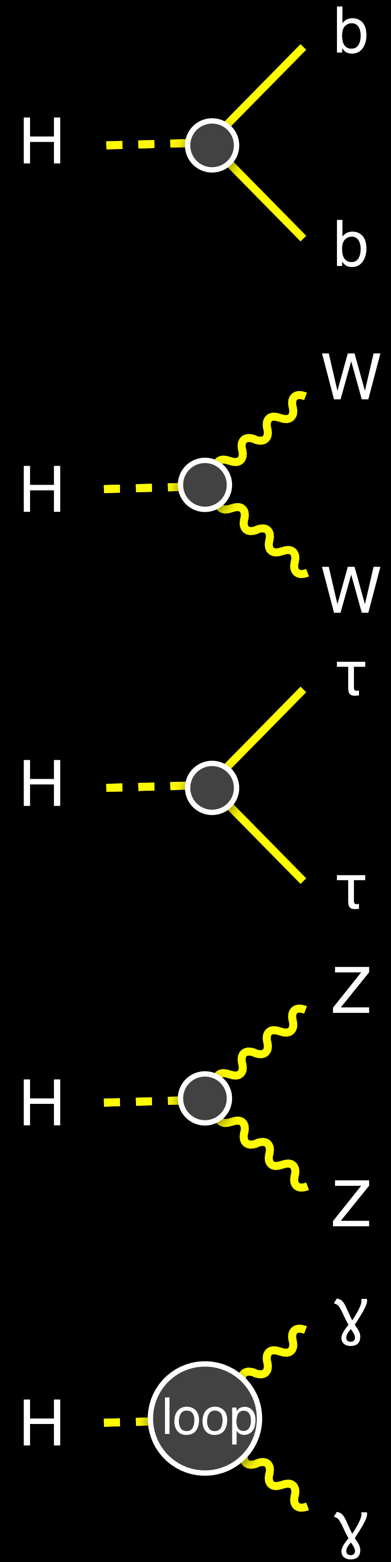
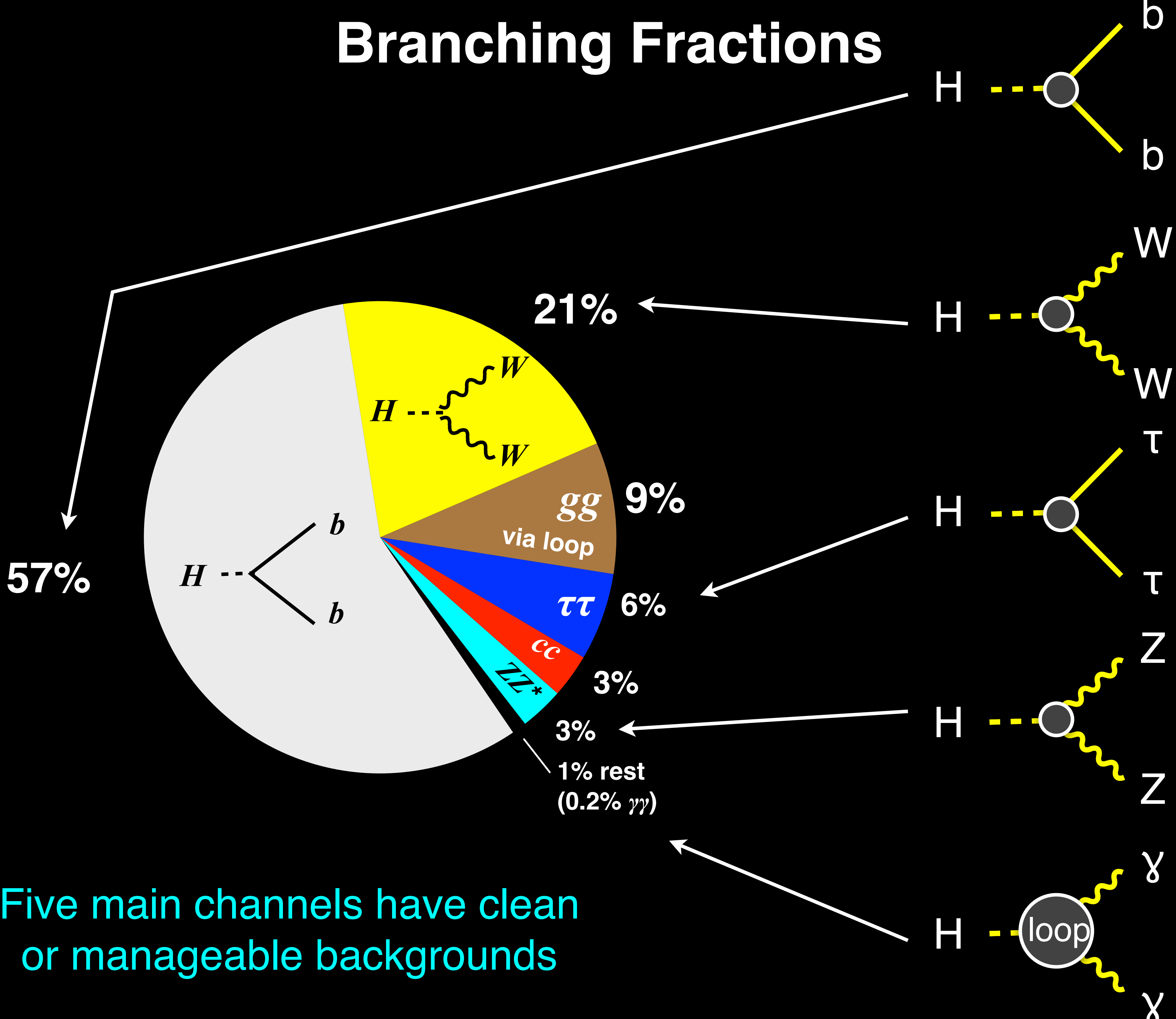




Five main channels have clean or manageable backgrounds

Branching Fractions



Five main channels have clean
or manageable backgrounds

Wait Higgs to photons…?

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How? photons do not have mass
⇒ no coupling to Higgs

Wait Higgs to photons…?

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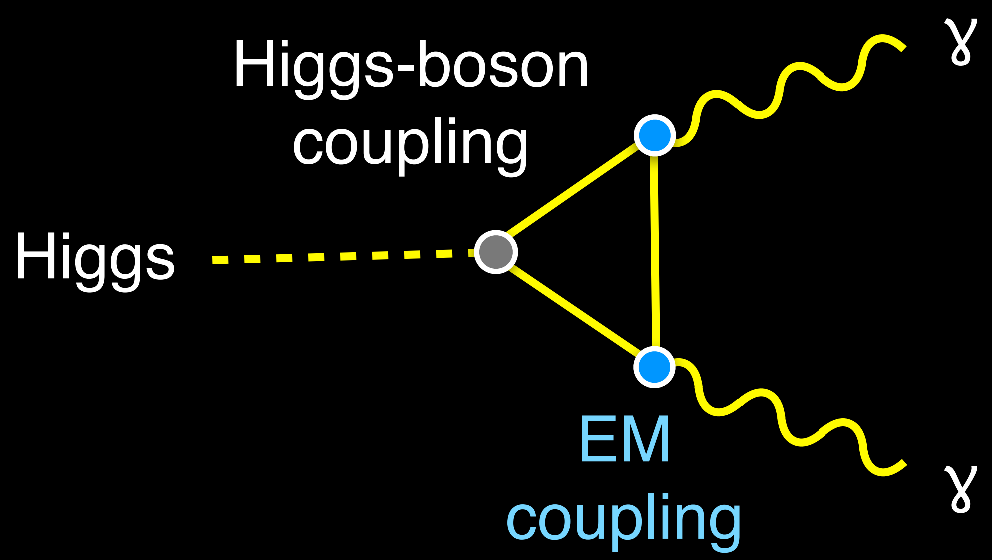
How? photons do not have mass
⇒ no coupling to Higgs



Wait Higgs to photons…?

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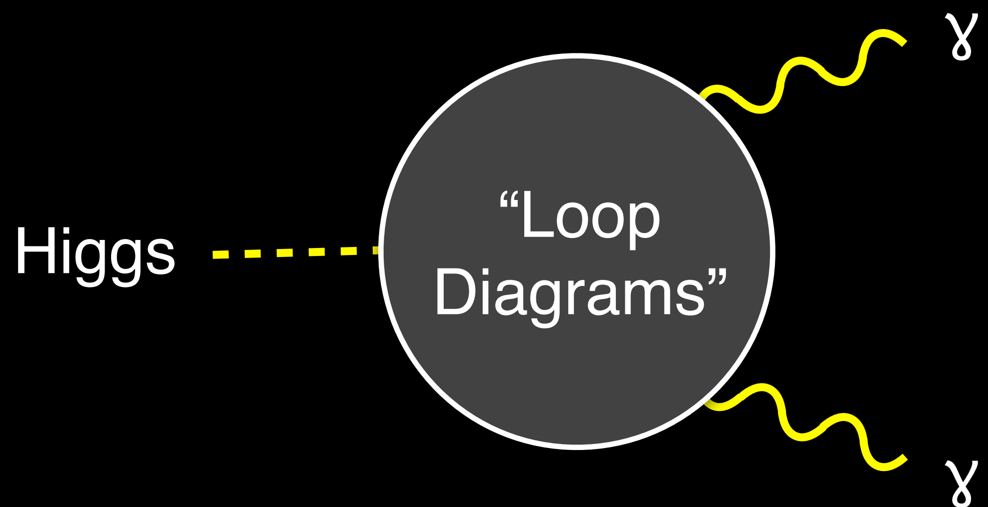
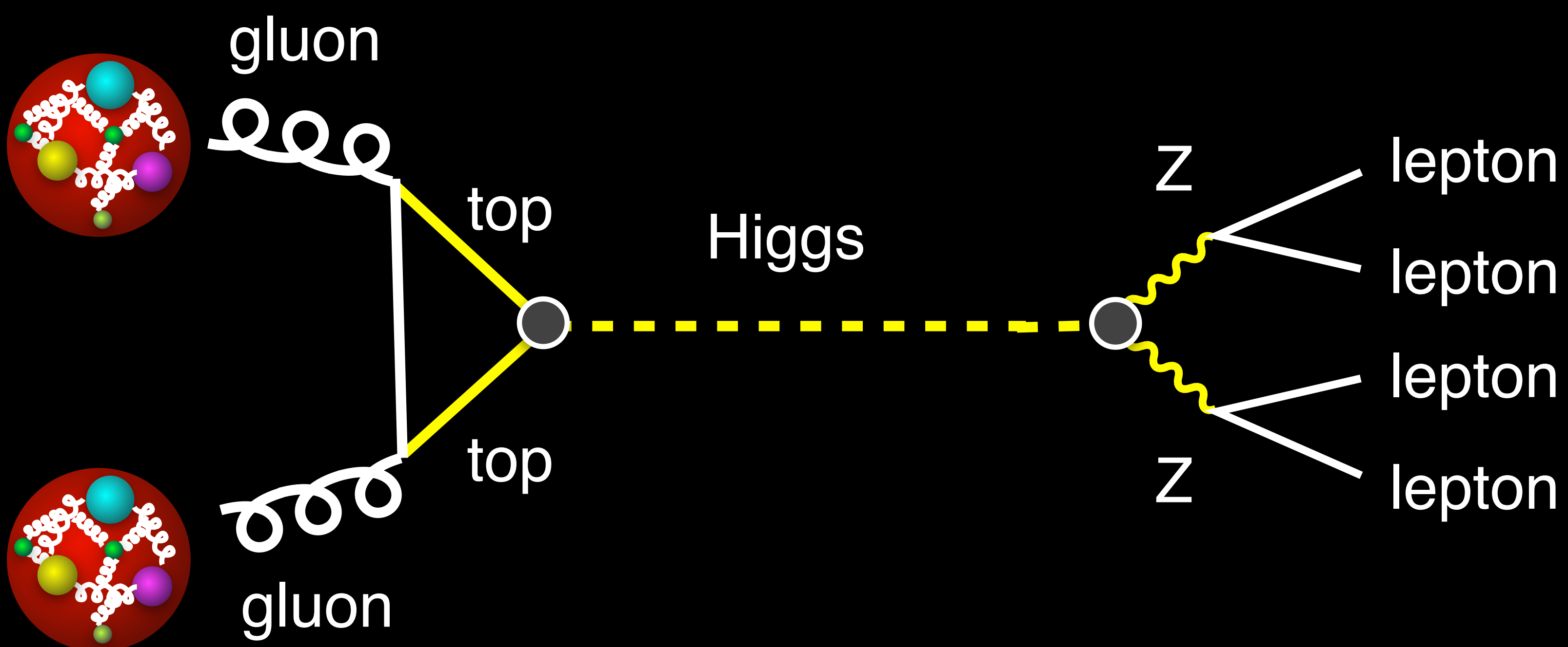
How? photons do not have mass
⇒ no coupling to Higgs



There are more…

Example channel H→ZZ→llll



~20000 per 1 fb^{-1} × 3% × 1% = 6 per 1 fb^{-1}

Reconstructing leptons

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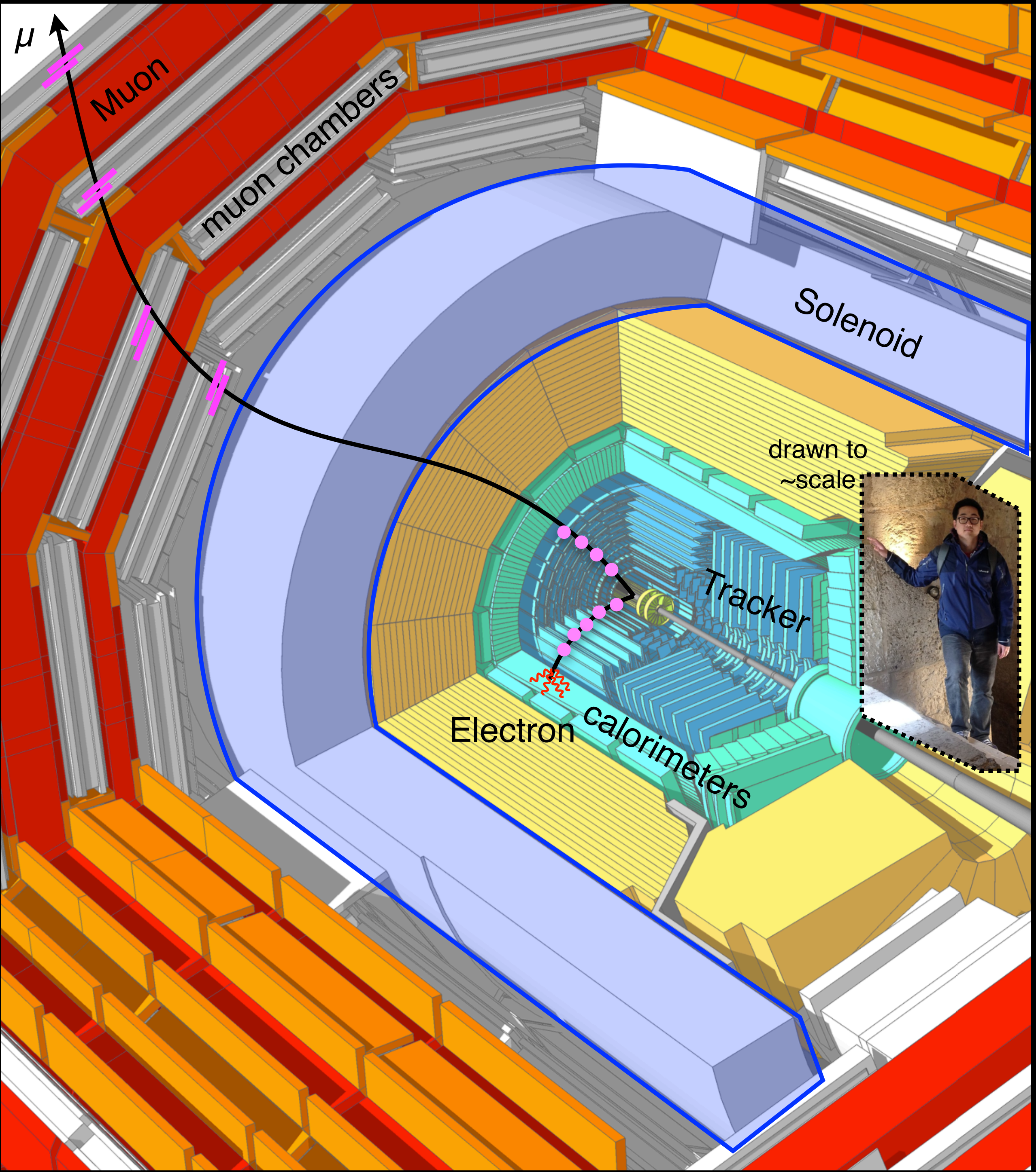

Despite its good reconstruction per lepton ~80-90% efficient

Leads to inefficiencies

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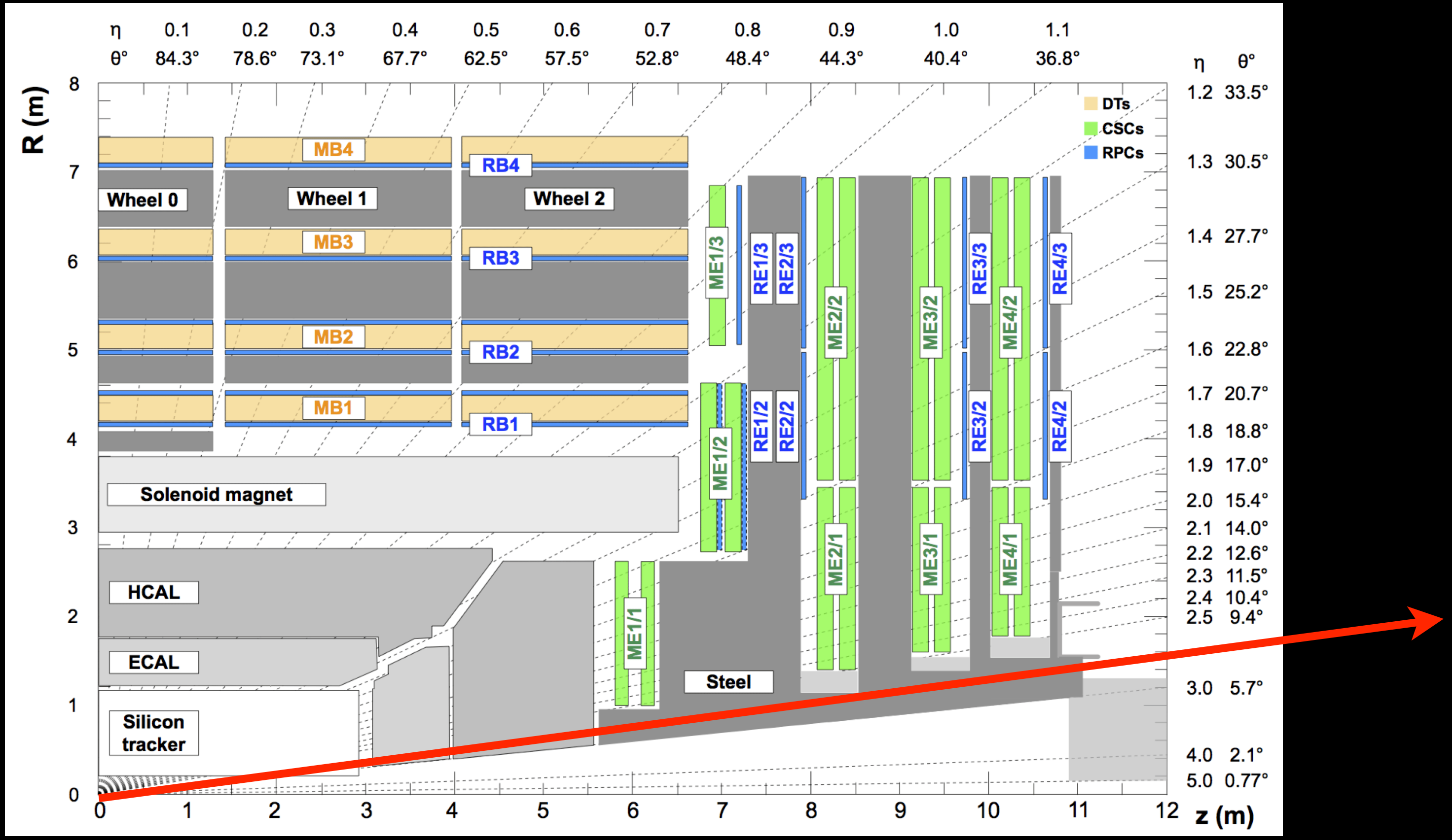
And some leptons may get outside of detector acceptance



Further leads to inefficiencies

Higgs boson discovery

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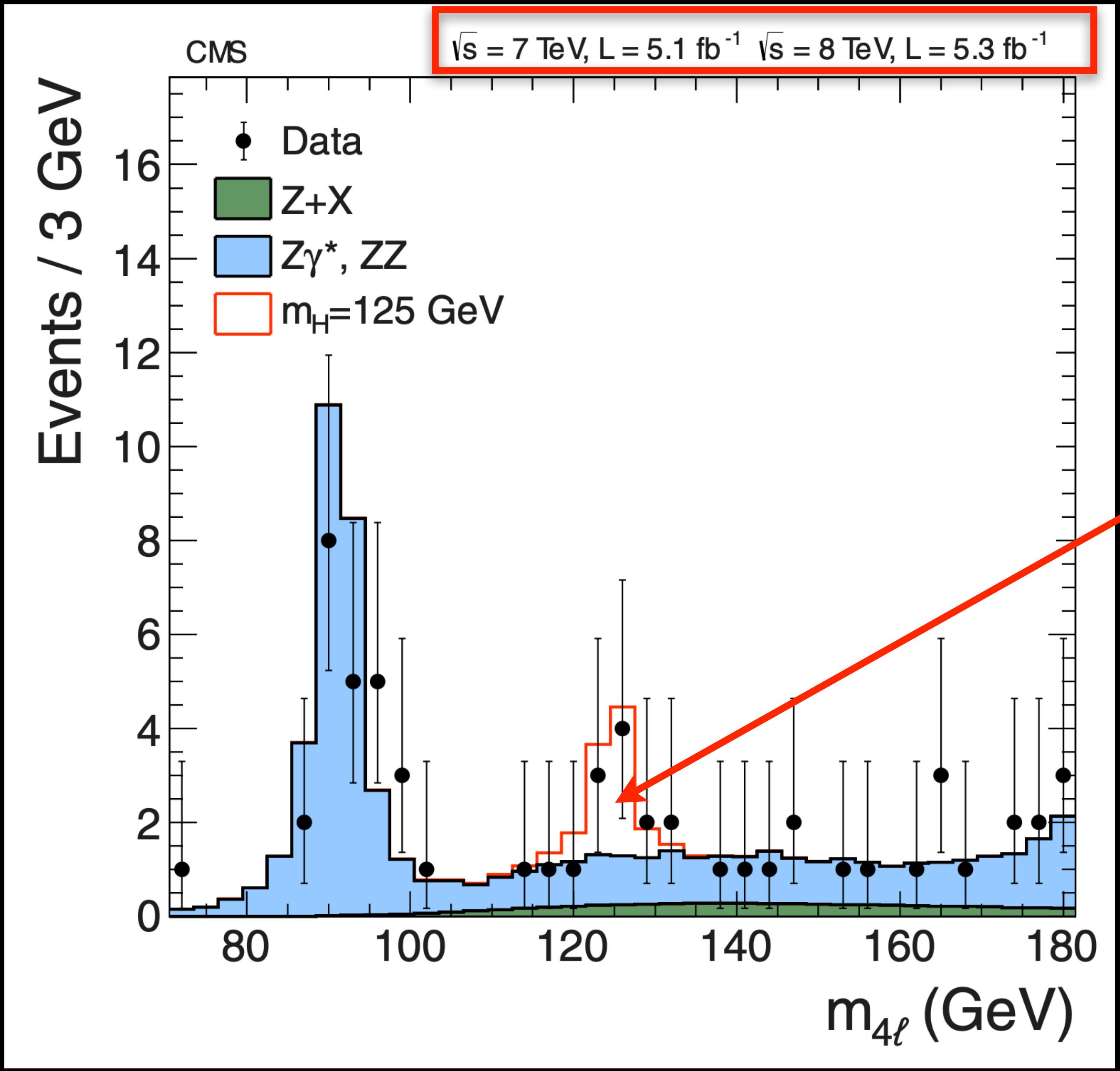


~ 10 fb^{-1}

⇒ ~60 expected

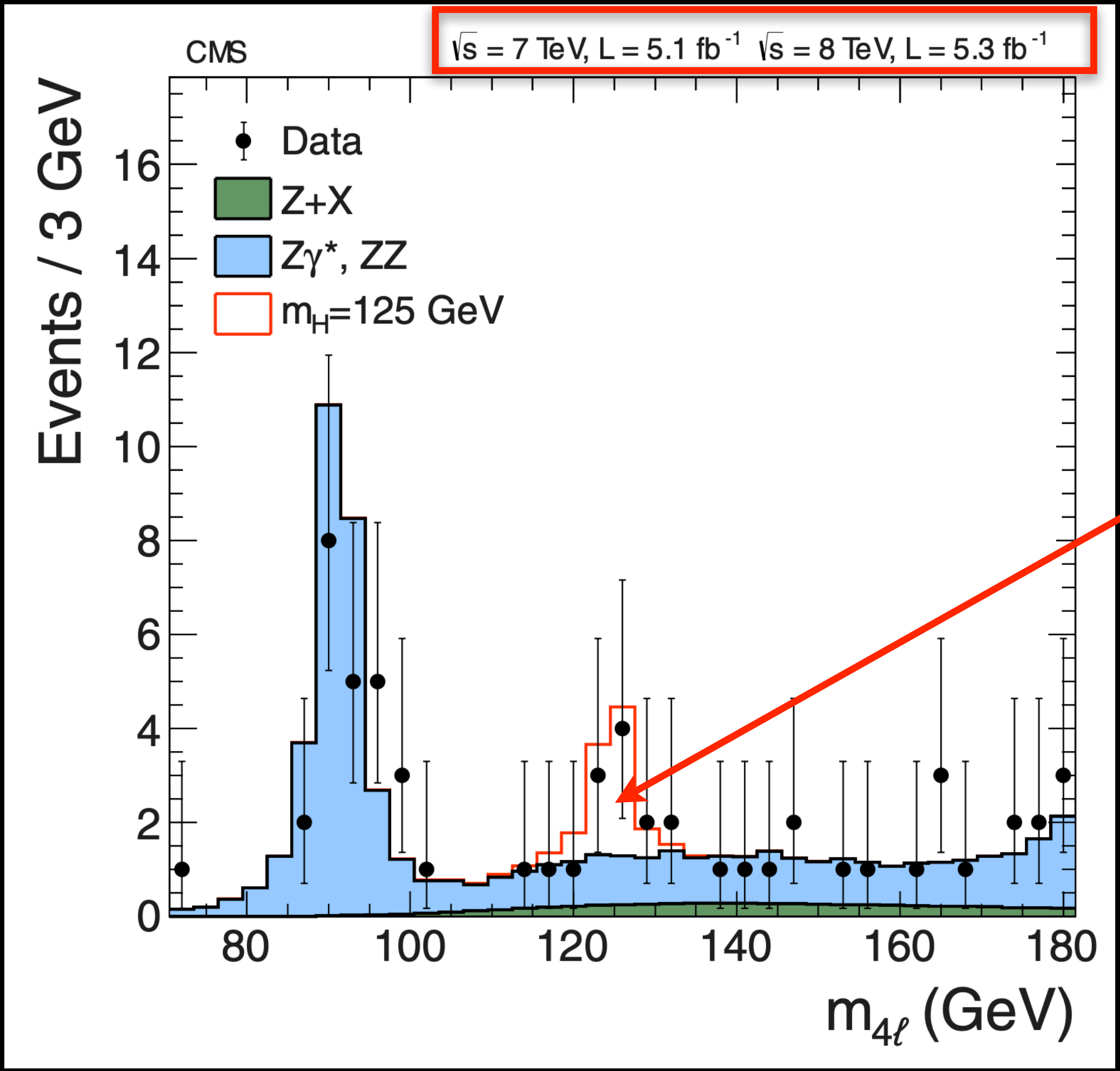
7.54 events

Per lepton
~ 60% eff. × acc.
(on average*)

$60 \times (60\%)^4 = 7.8$

* ignoring various other phase-space selection for simplicity

Higgs boson discovery



From theory

7.54 events

Observed ~ 9 data events

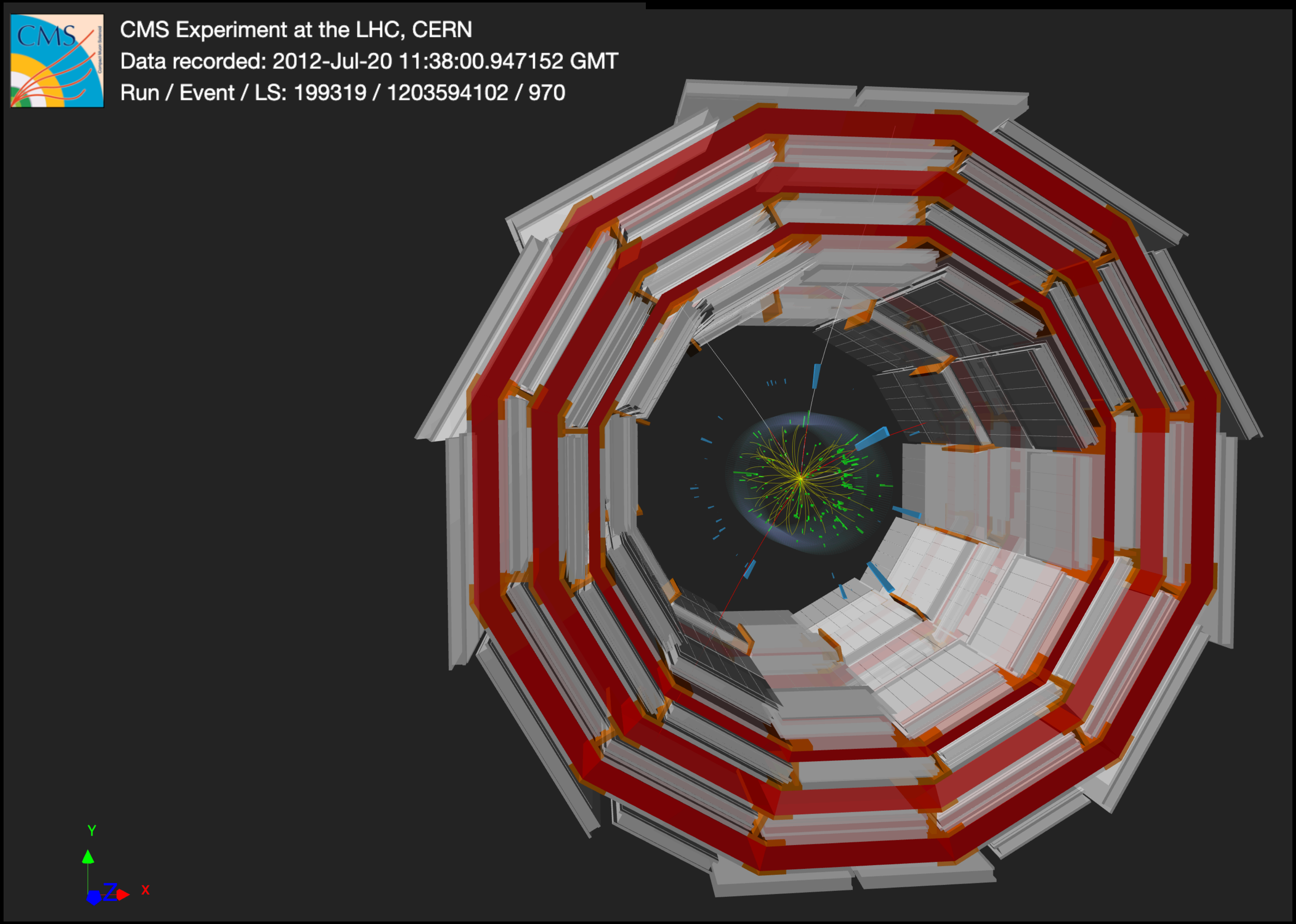
Bkg ~ 3.5 events

Observed signal = 5.5 evt

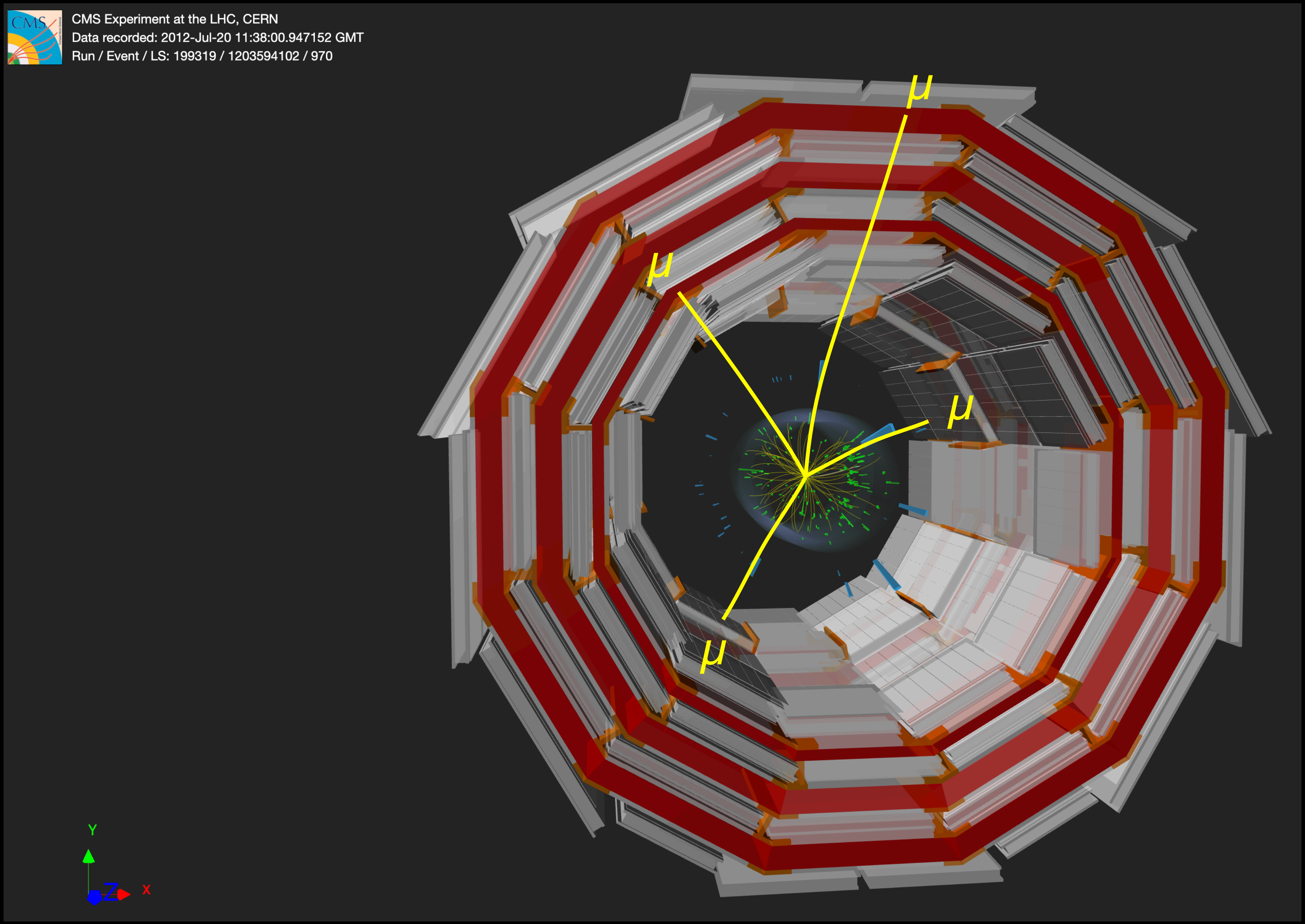
What can we learn from this?

* ignoring various other phase-space selection for simplicity

Event display



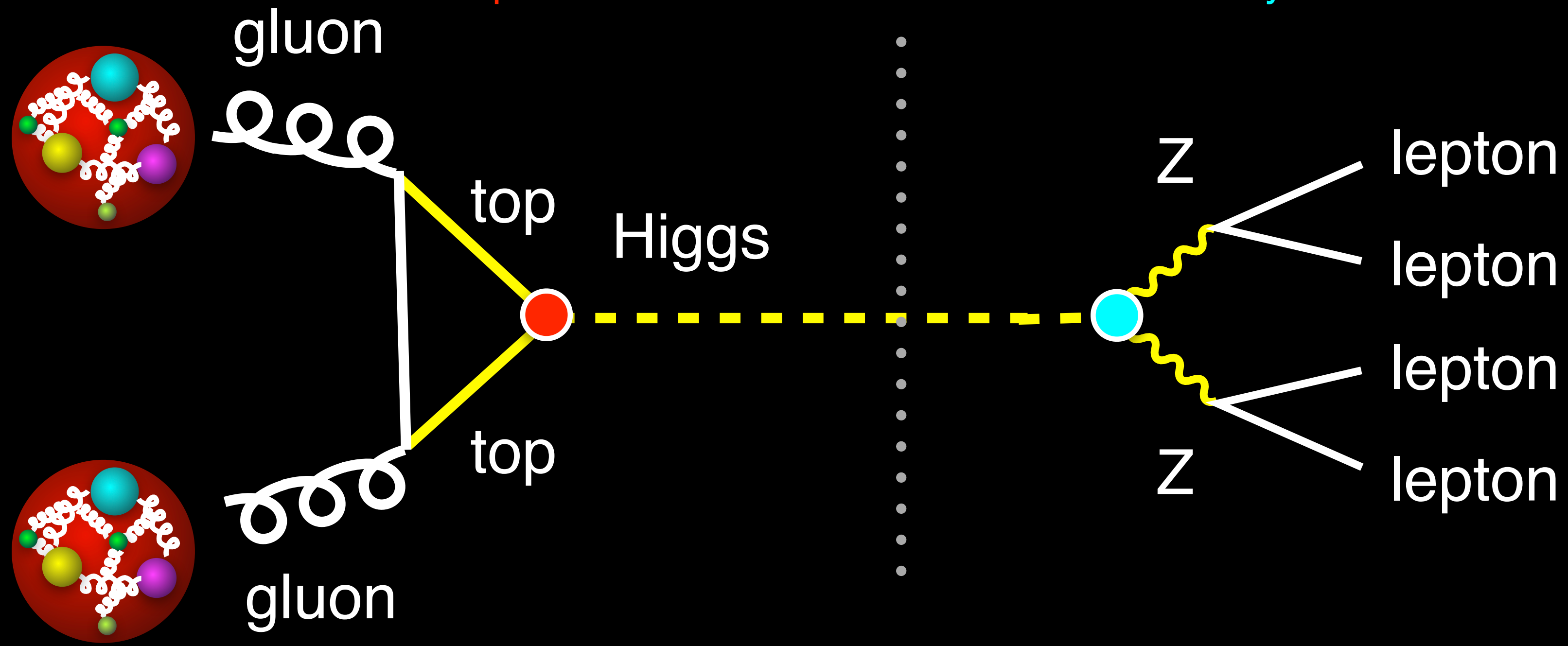
Title


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2012-Jul-20 11:38:00.947152 GMT
Run / Event / LS: 199319 / 1203594102 / 970
μ
μ
μ
μ
Y
Z
X

Rate ~ Production and Decay

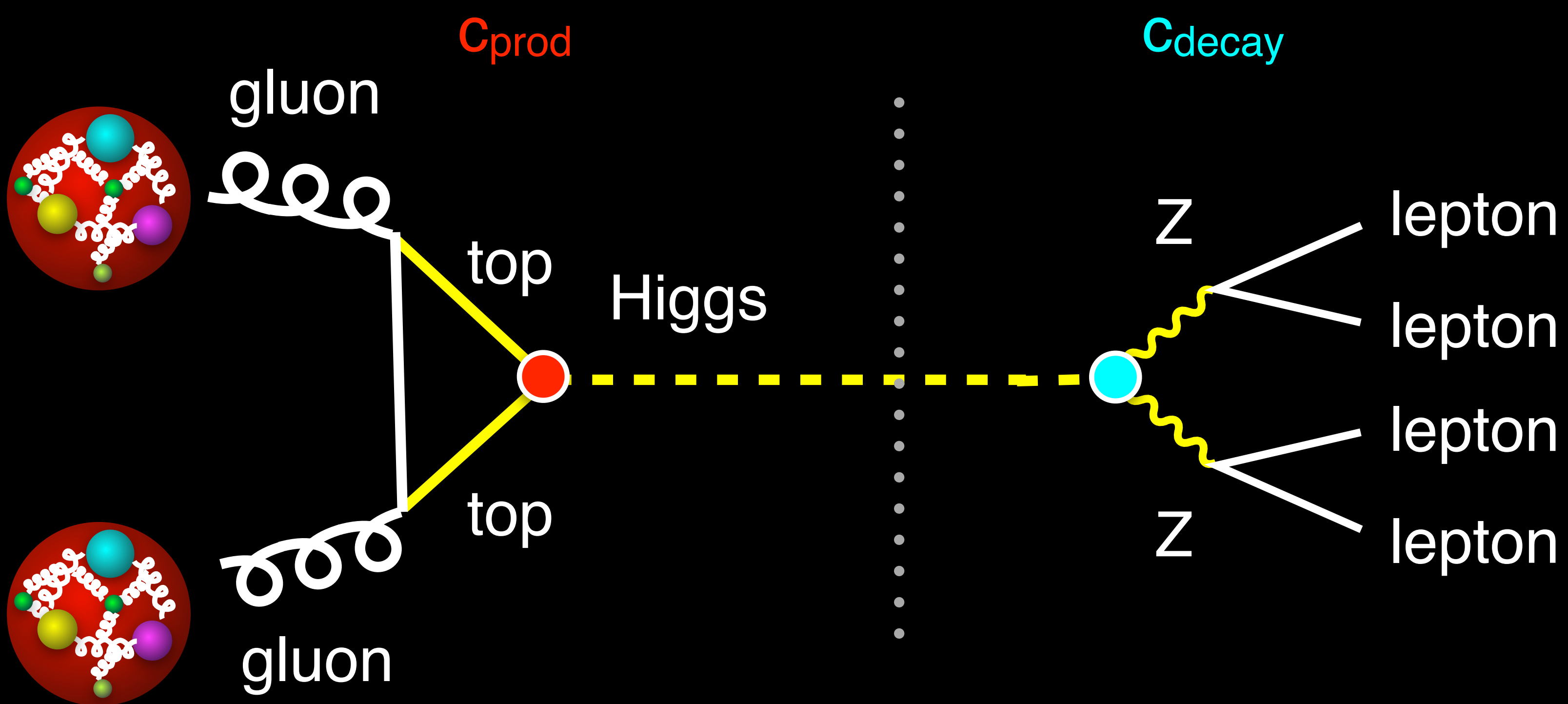
Production coupling c_{prod}

Decay coupling c_{decay}



Rate ~ Production and Decay

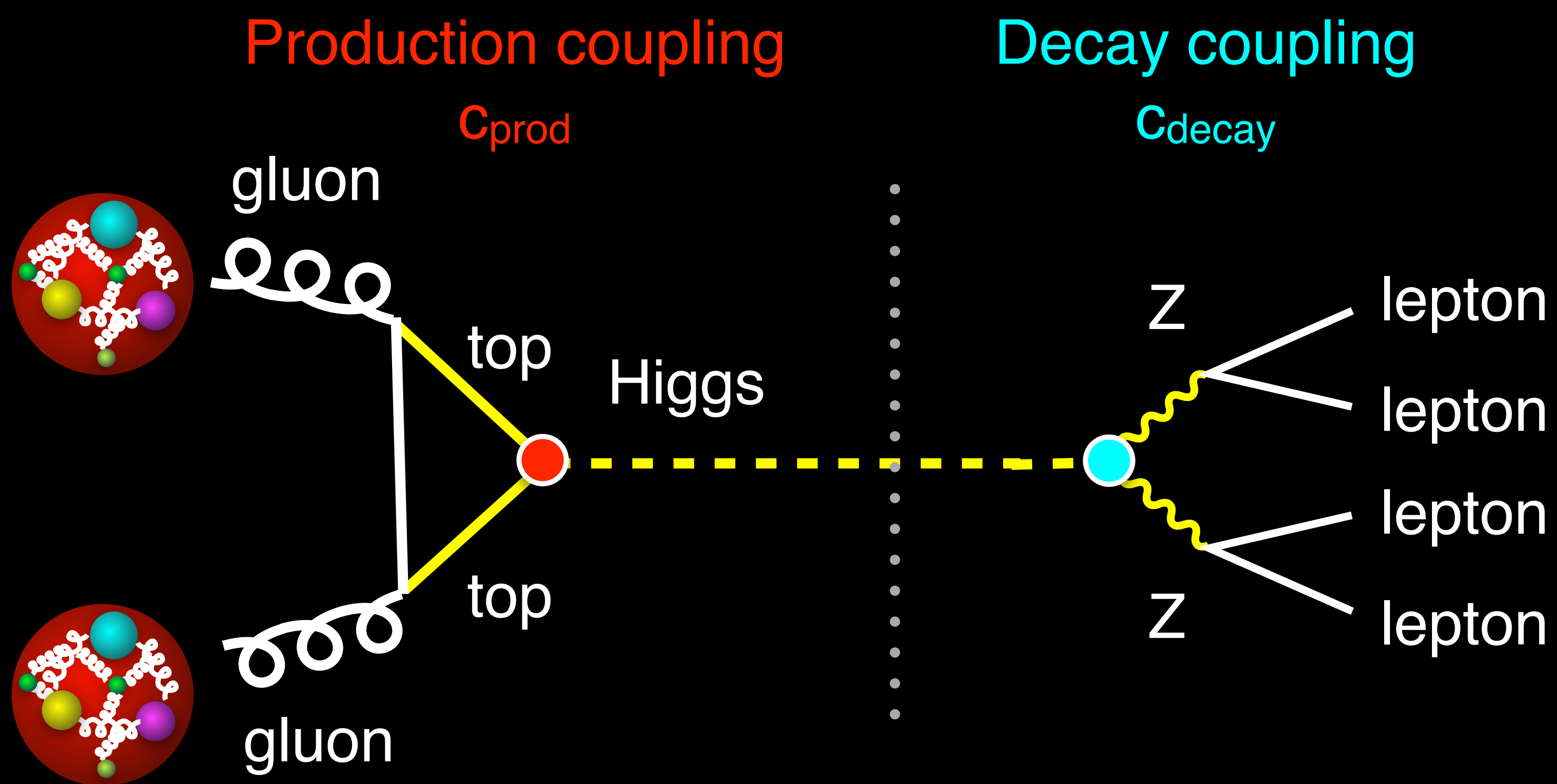
Production coupling | Decay coupling



Amplitude ~ $c_{prod}\, c_{decay}$

Rate ~ Amplitude² ~ $c_{prod}^2\, c_{decay}^2$

Rate ~ Production and Decay

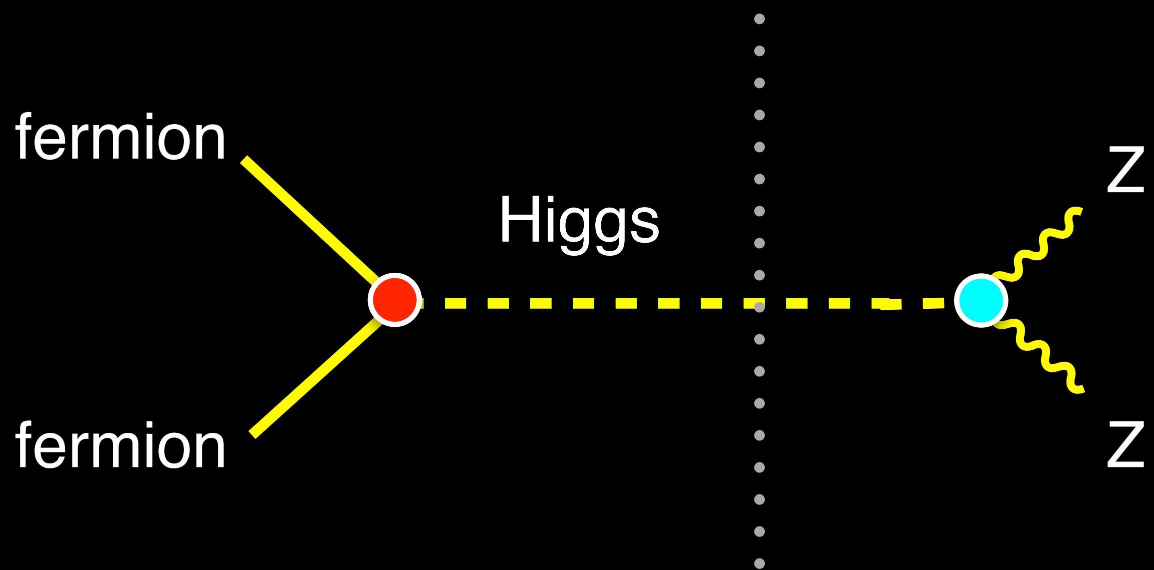


Amplitude ~ $c_{prod}\ c_{decay}$

Rate ~ Amplitude² ~ $c_{prod}^2\ c_{decay}^2$

Observing 5.5 events vs. 7.5 predicted events tells you something about c_{prod}/c_{decay}!

One measurement



$$\frac{\text{Rate observed} \sim c_{\text{prod,observed}}^2 \, c_{\text{decay,observed}}^2 \sim 5.5 \text{ events}}{\text{Rate predicted} \sim c_{\text{prod,theory}}^2 \, c_{\text{decay,predicted}}^2 \sim 7.5 \text{ events}} = 0.73$$

You can’t tell which one is different from theory

Many measurements

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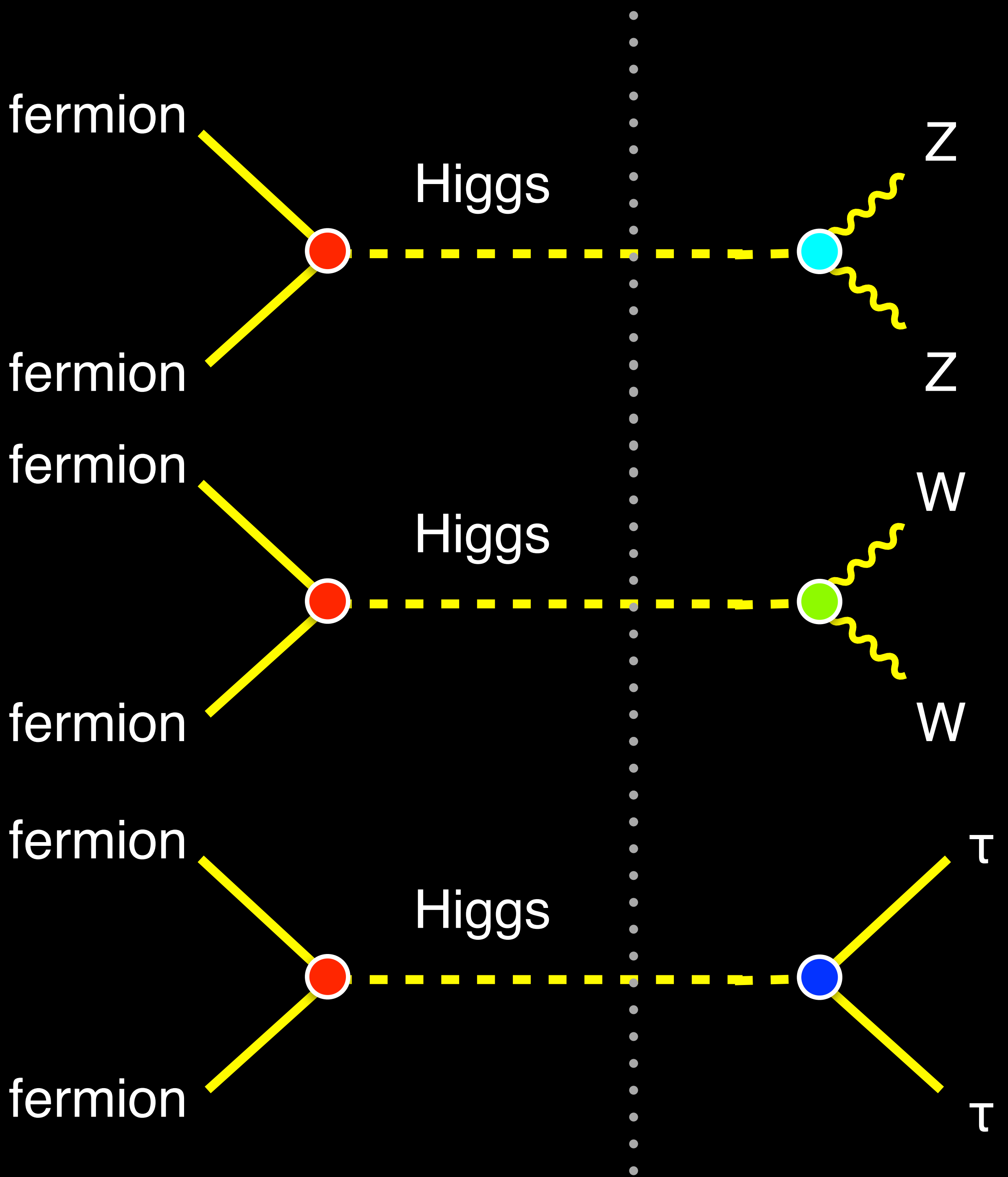
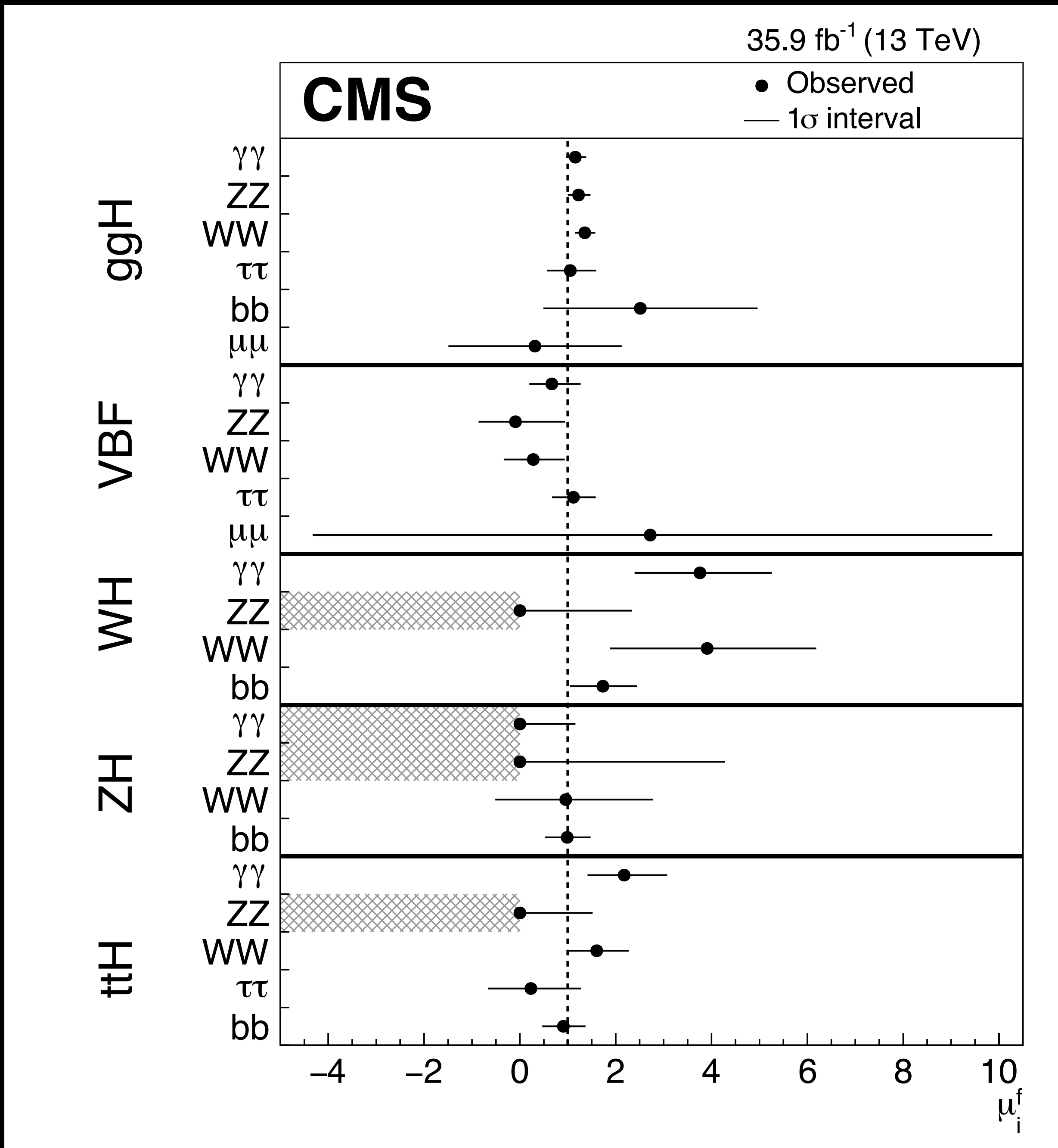


Ratio ~ 0.73

Ratio ~ 1.05

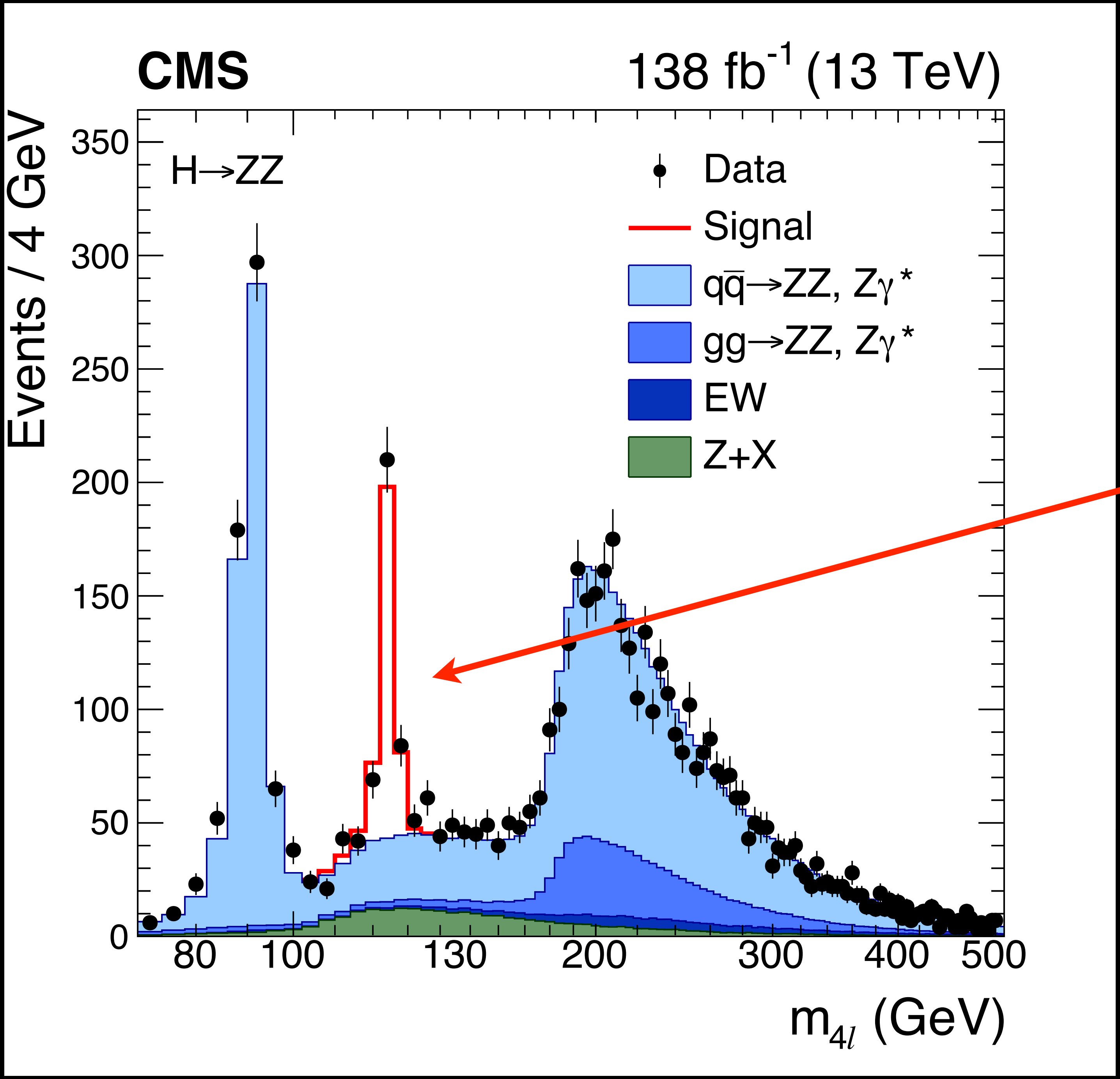
Ratio ~ 0.92

Various different rate measurements



Rate ~ $c_{prod}^2 \; c_{decay}^2$

Today



More sharp and clearer

Various different coupling measurements

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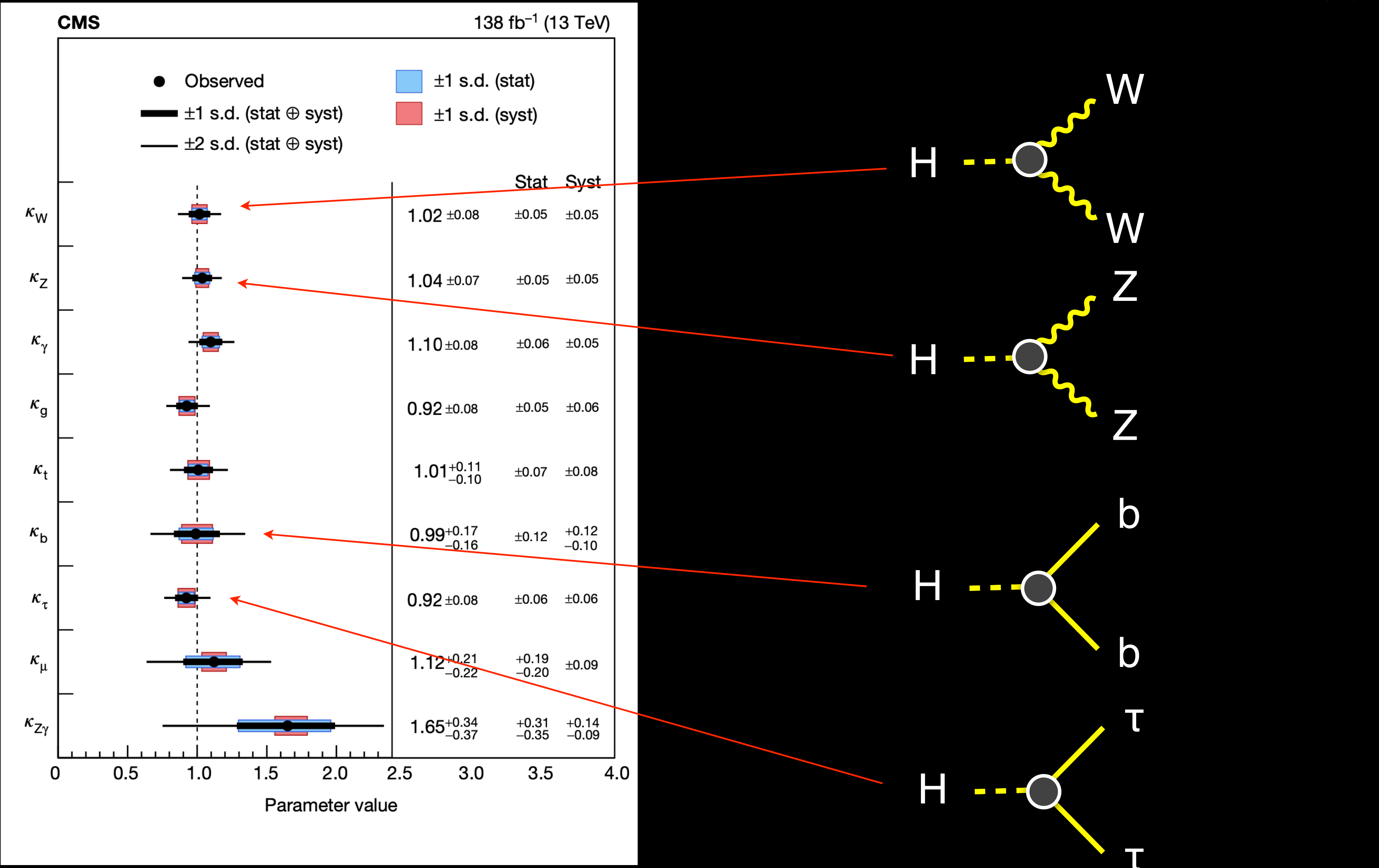

Various different coupling measurements

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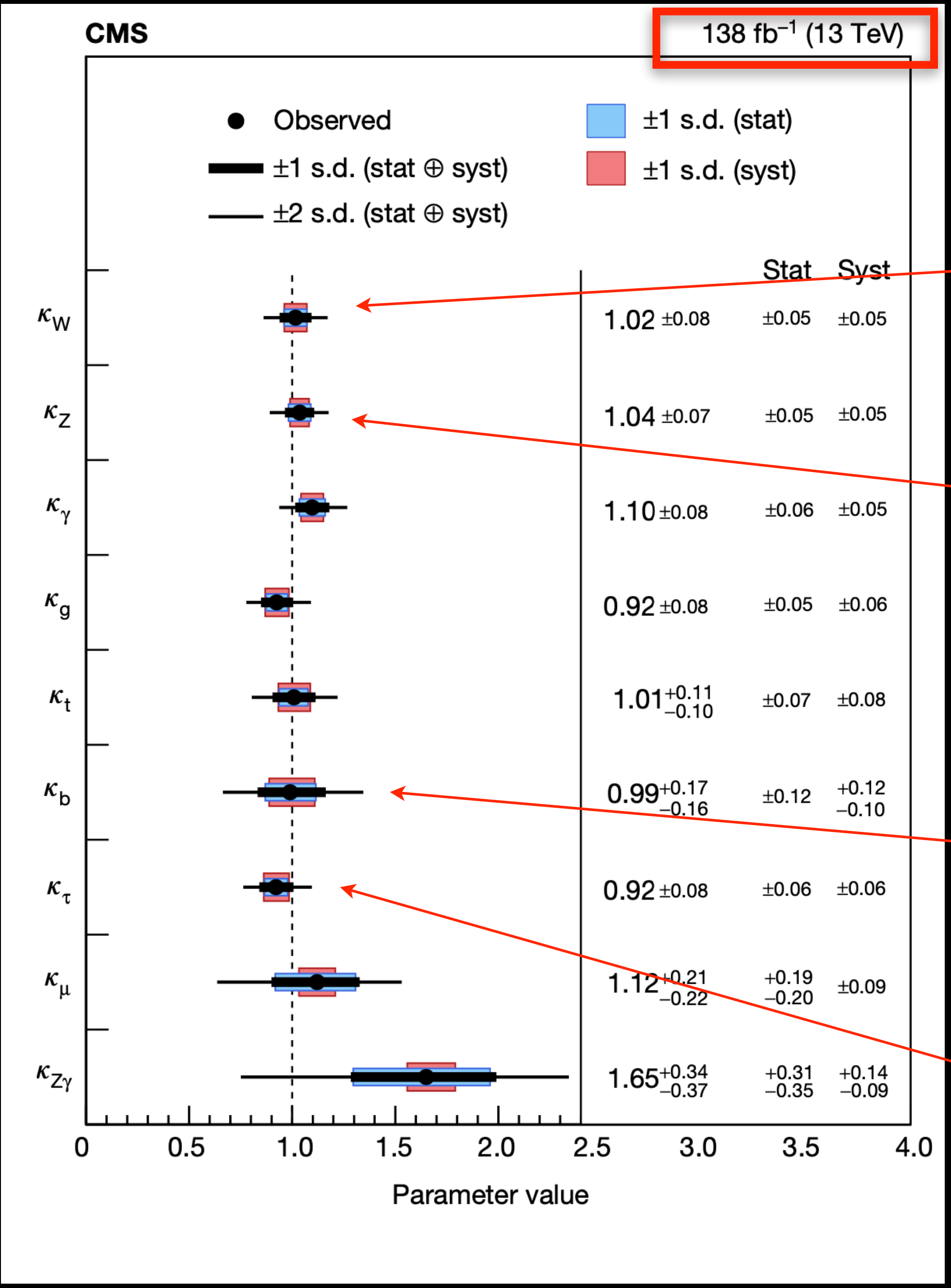
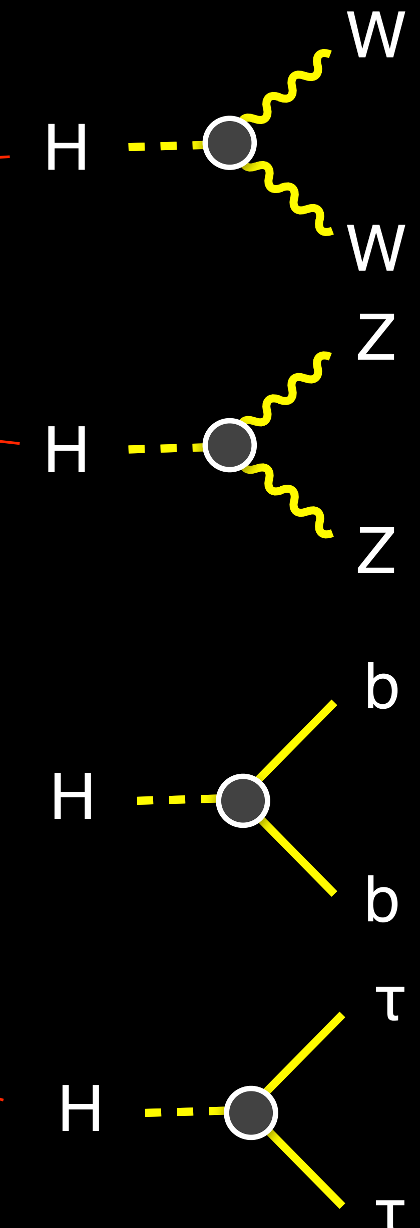
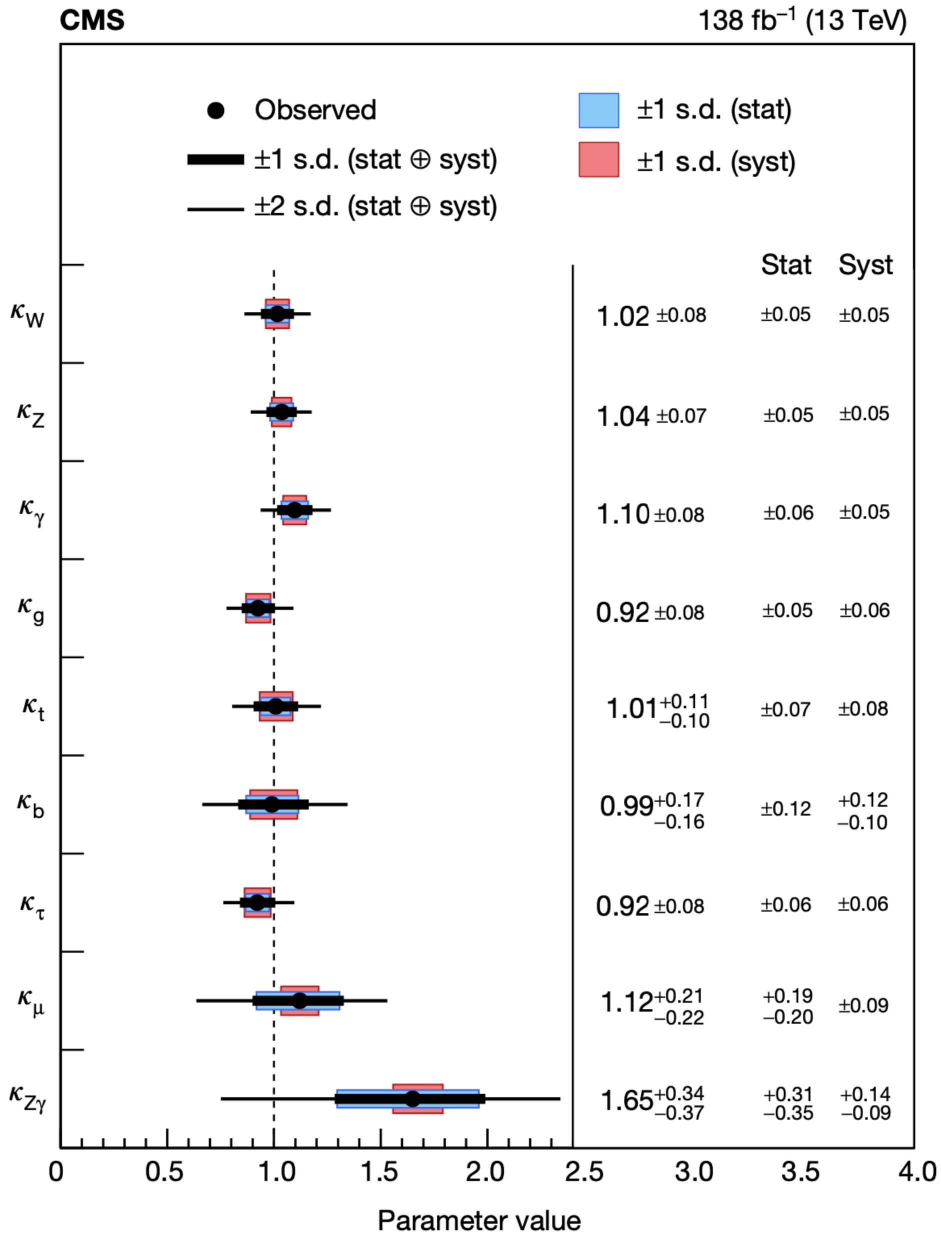
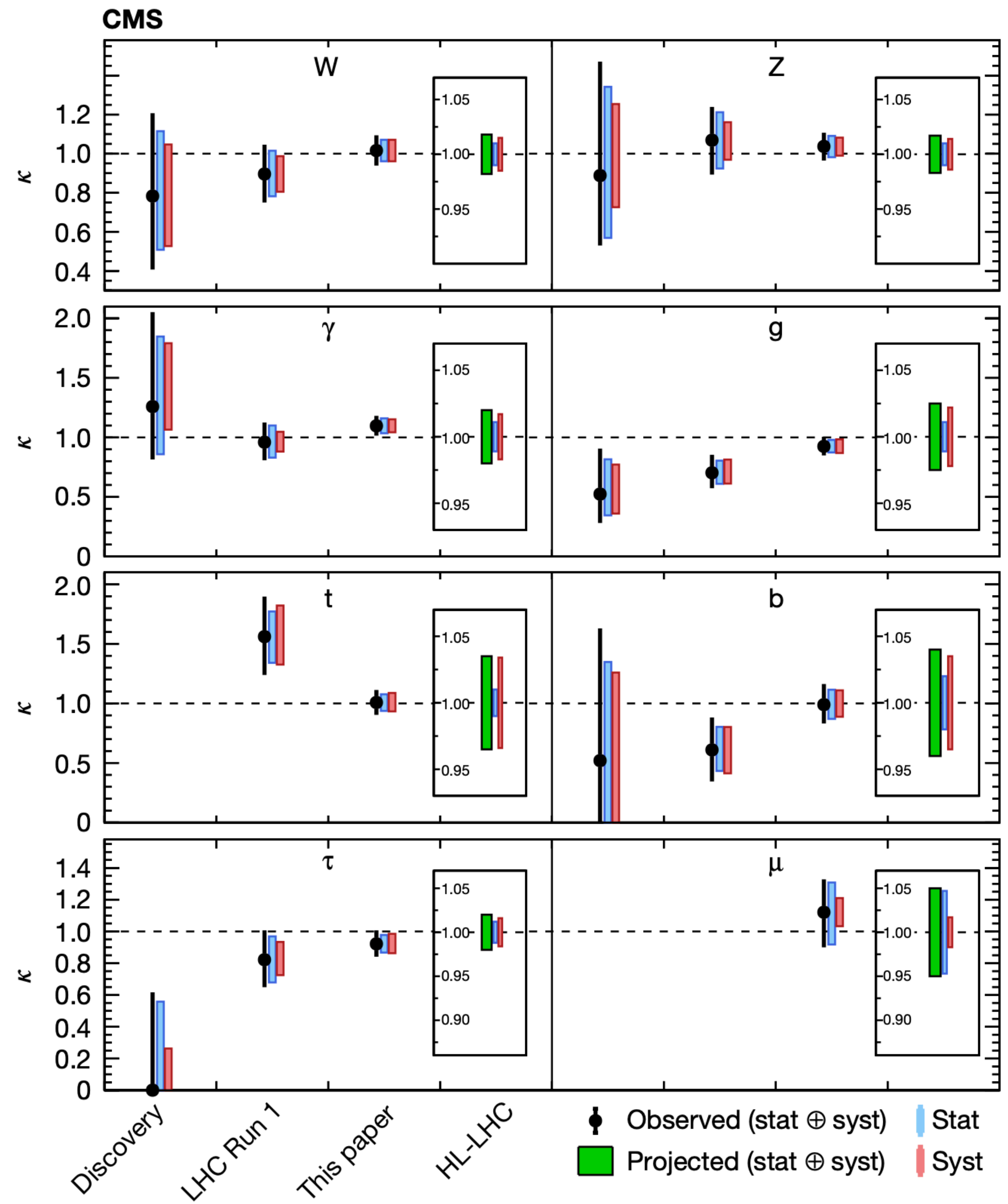
7M higgs





Future of coupling measurements





Future of coupling measurements

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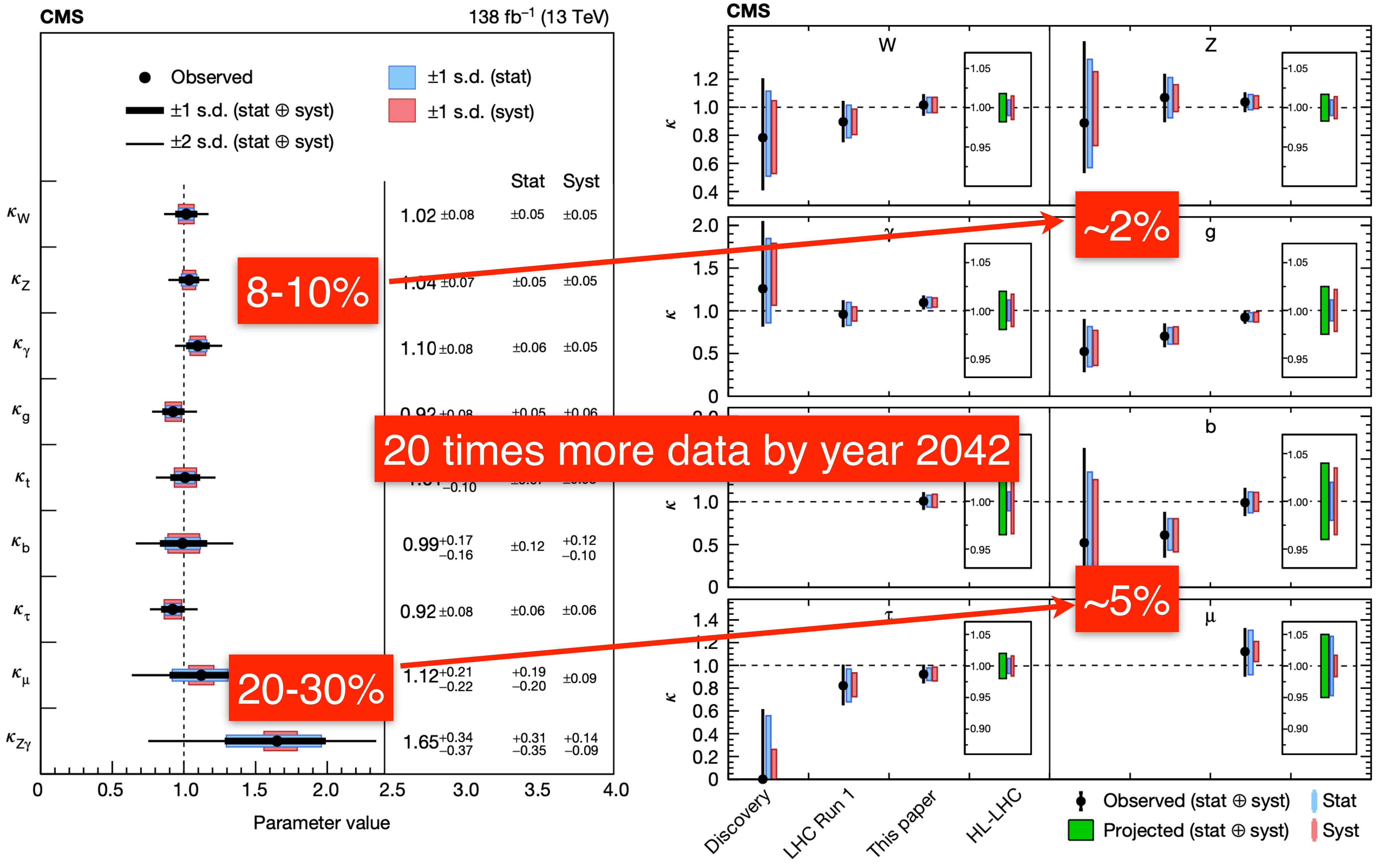
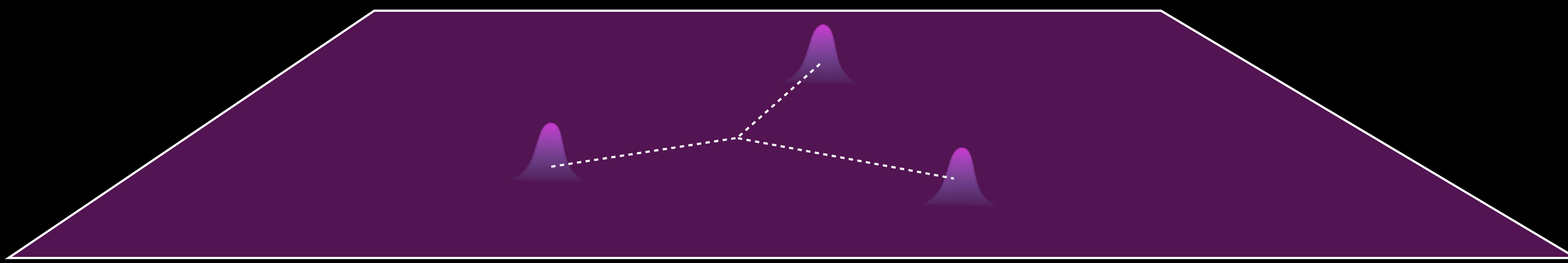


SM Lagrangian

Higgs Field



ϕ

And Higgs field is unique in that it *interacts* with itself

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation?language_content_entity=und

SM Lagrangian

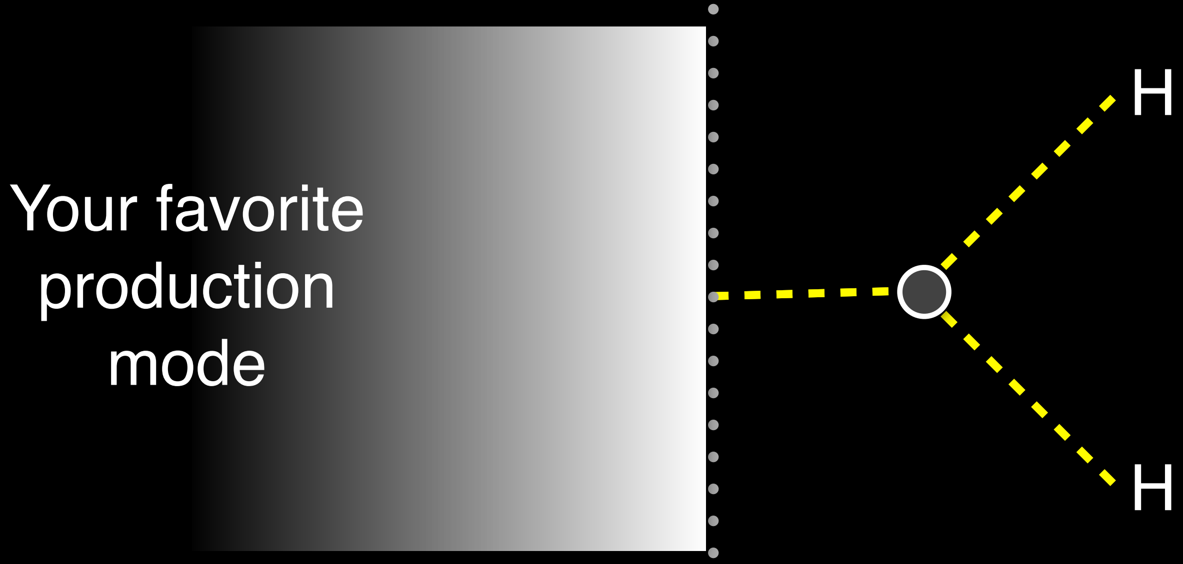
Higgs Field

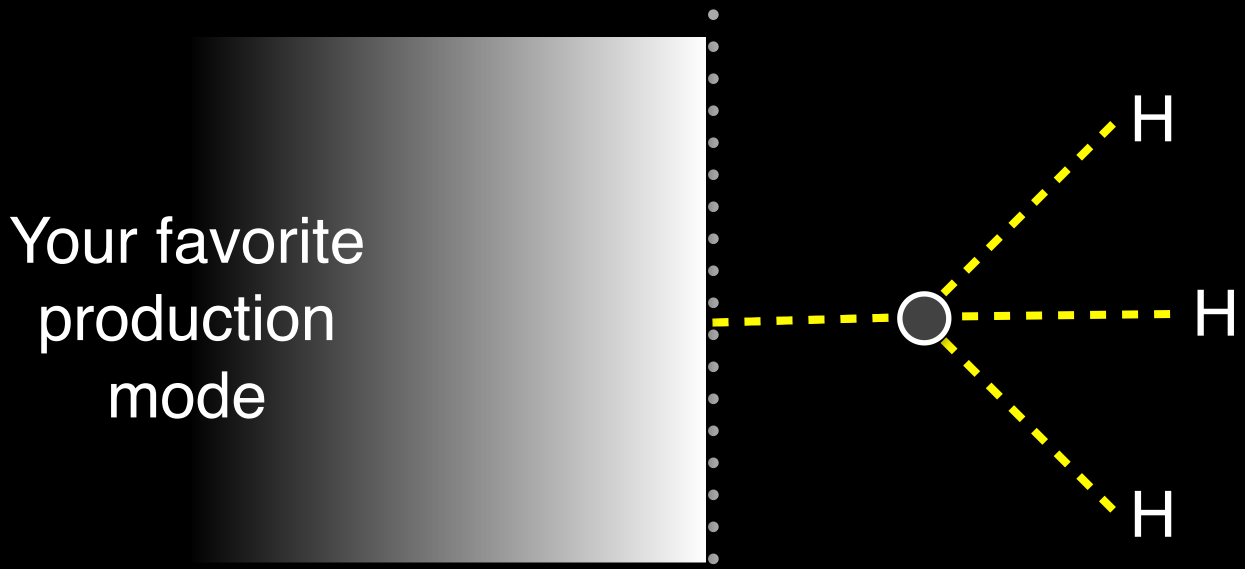
(ϕ' + Constant)

It results in *non-zero vacuum expectation value*

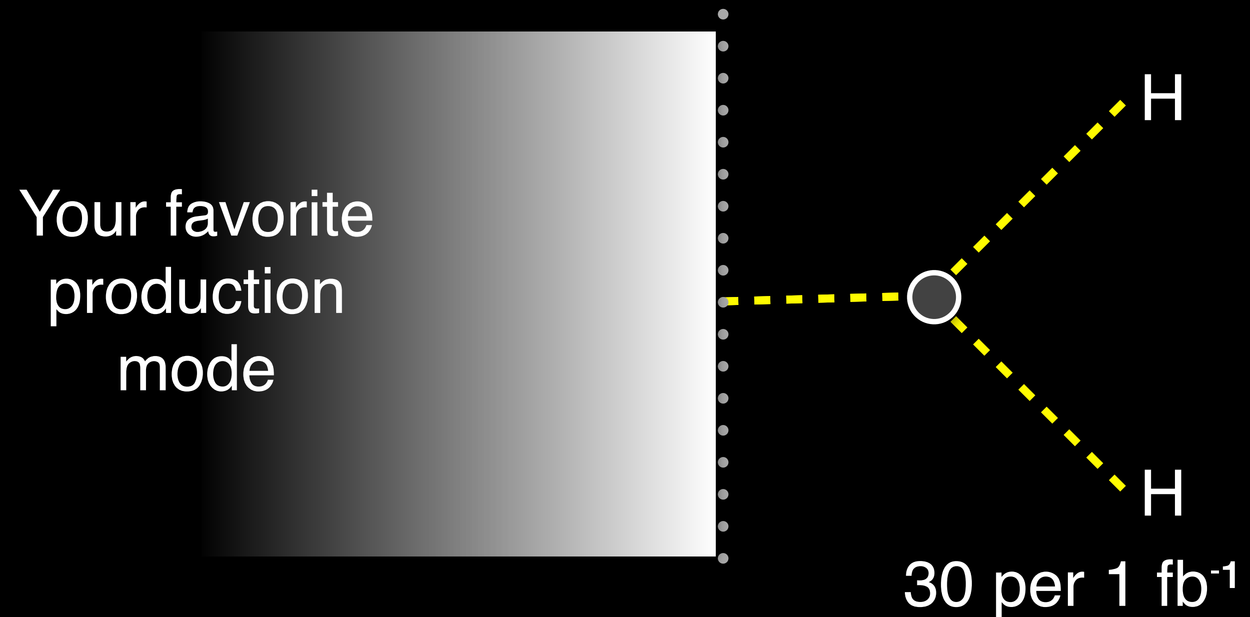

Why??

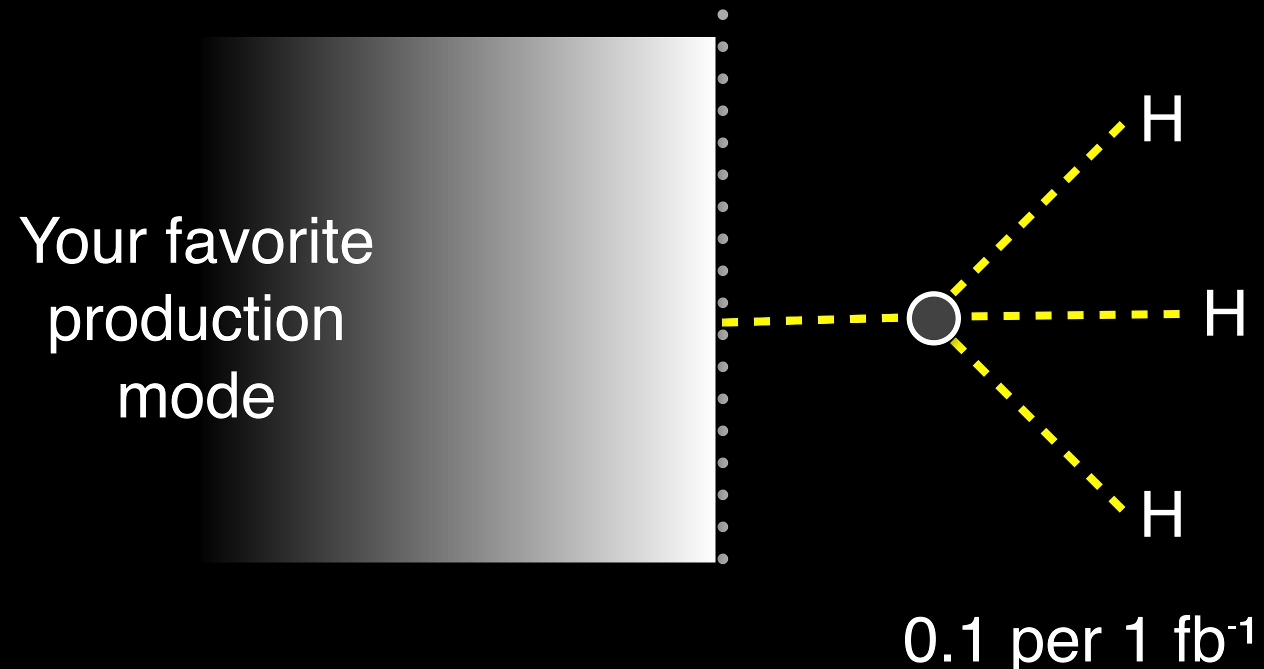
Higgs self-couplings



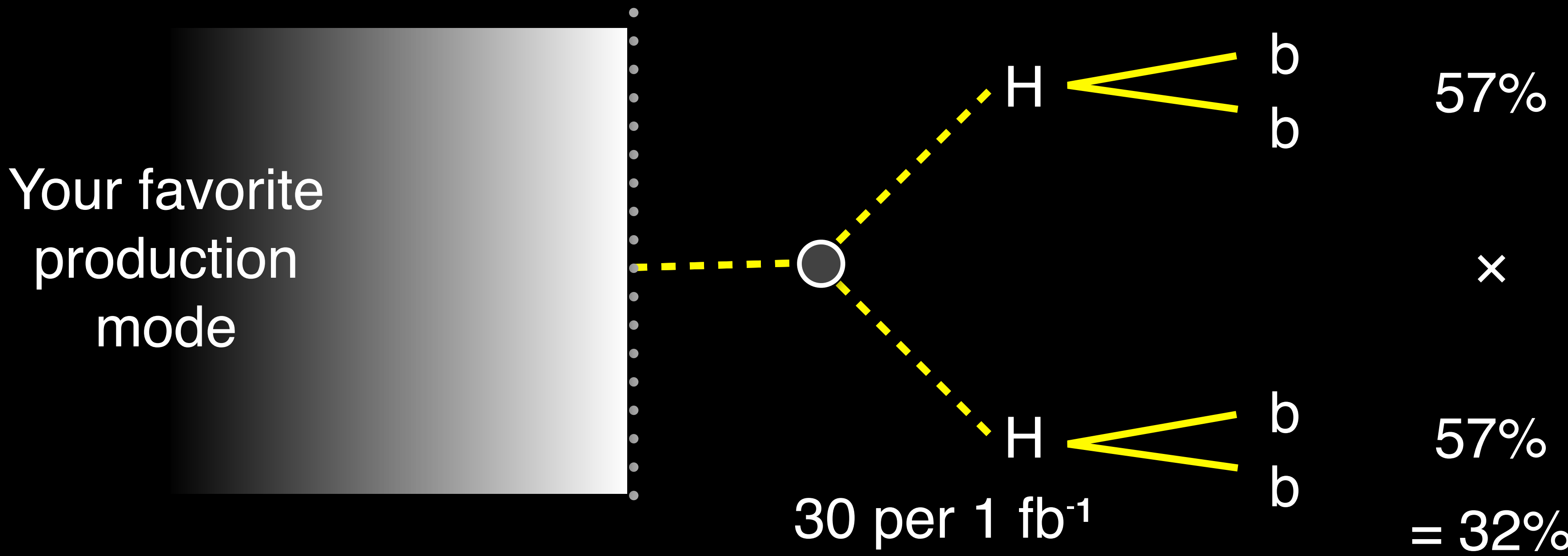


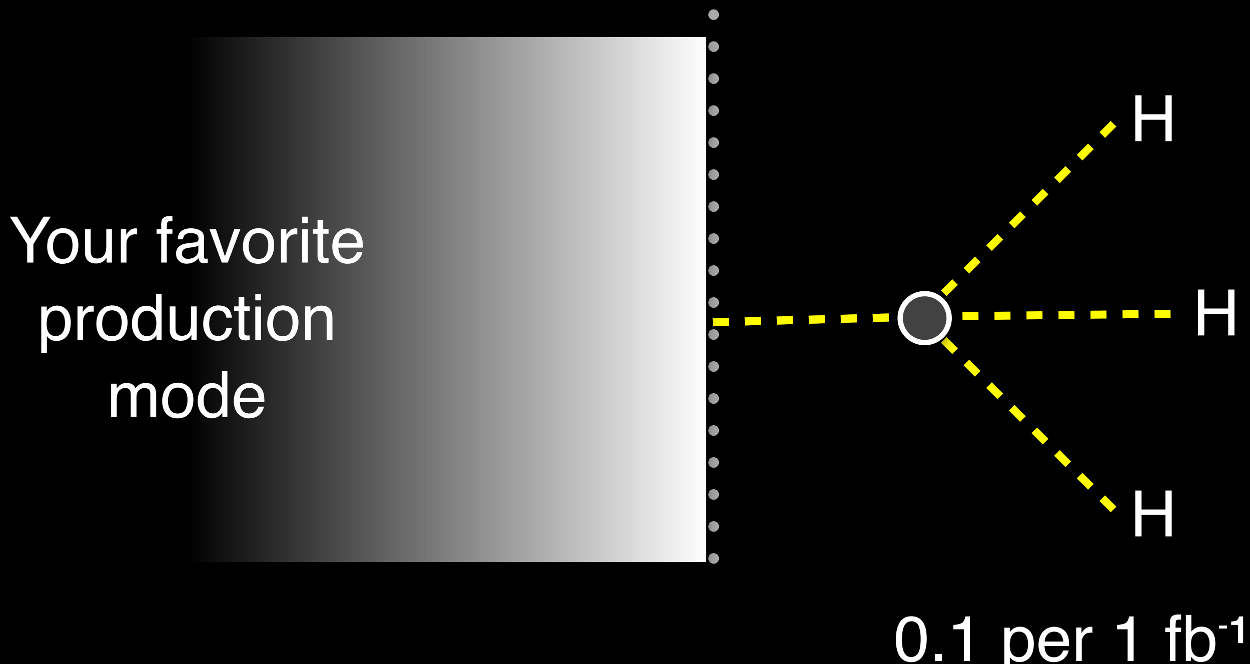
Higgs self-couplings



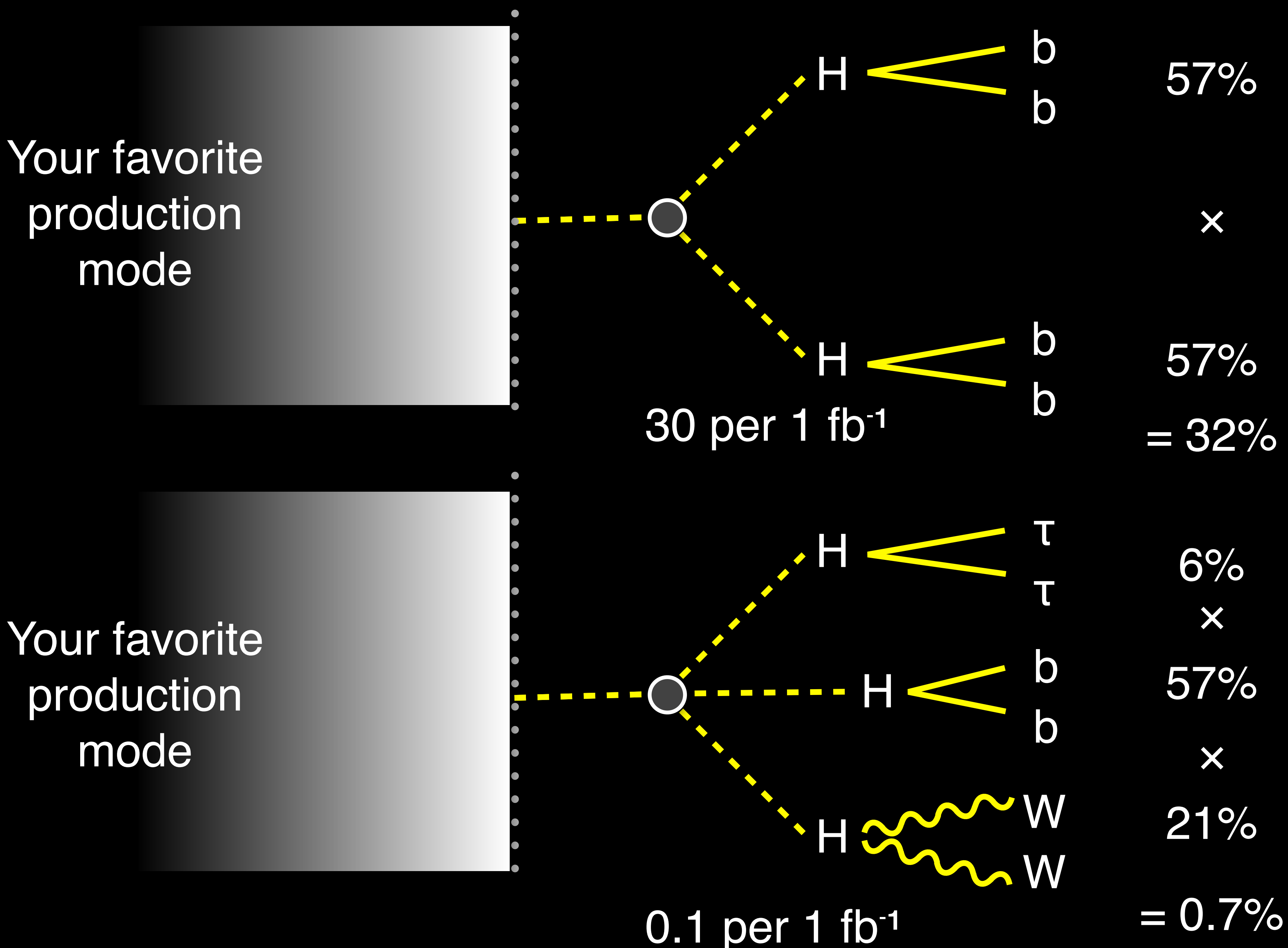


Higgs self-couplings

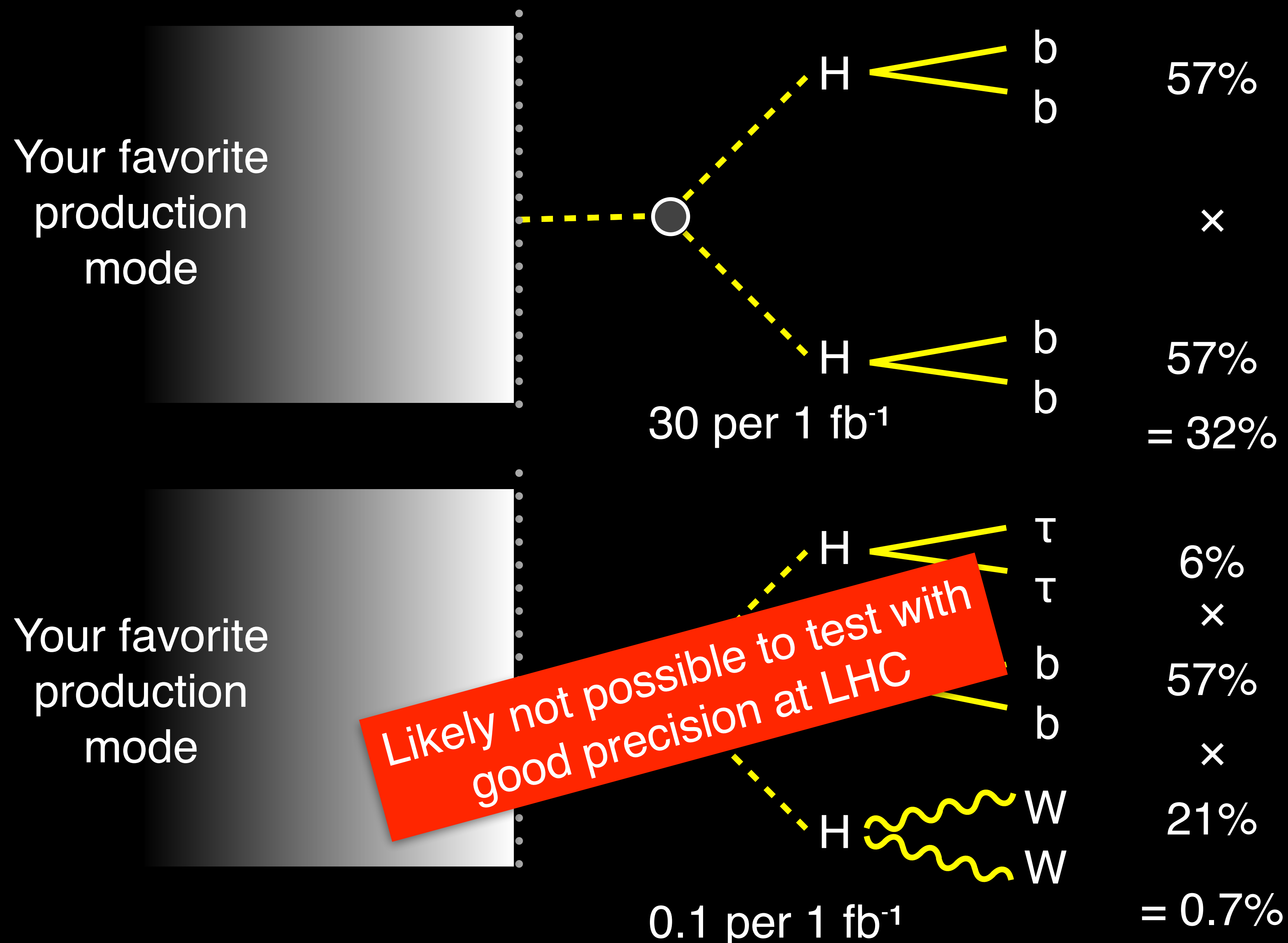




Higgs self-couplings



Higgs self-couplings



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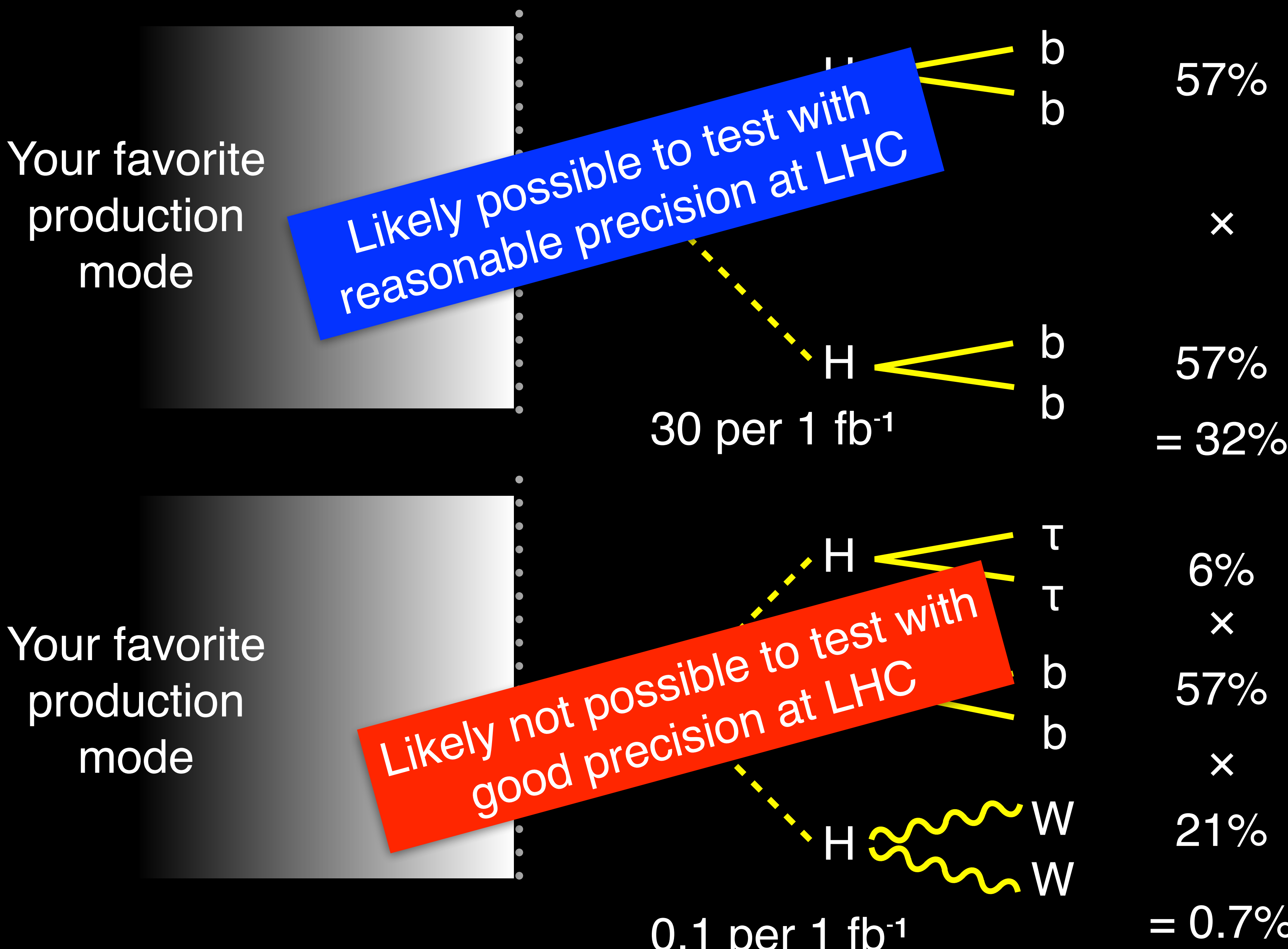

Higgs self-coupling

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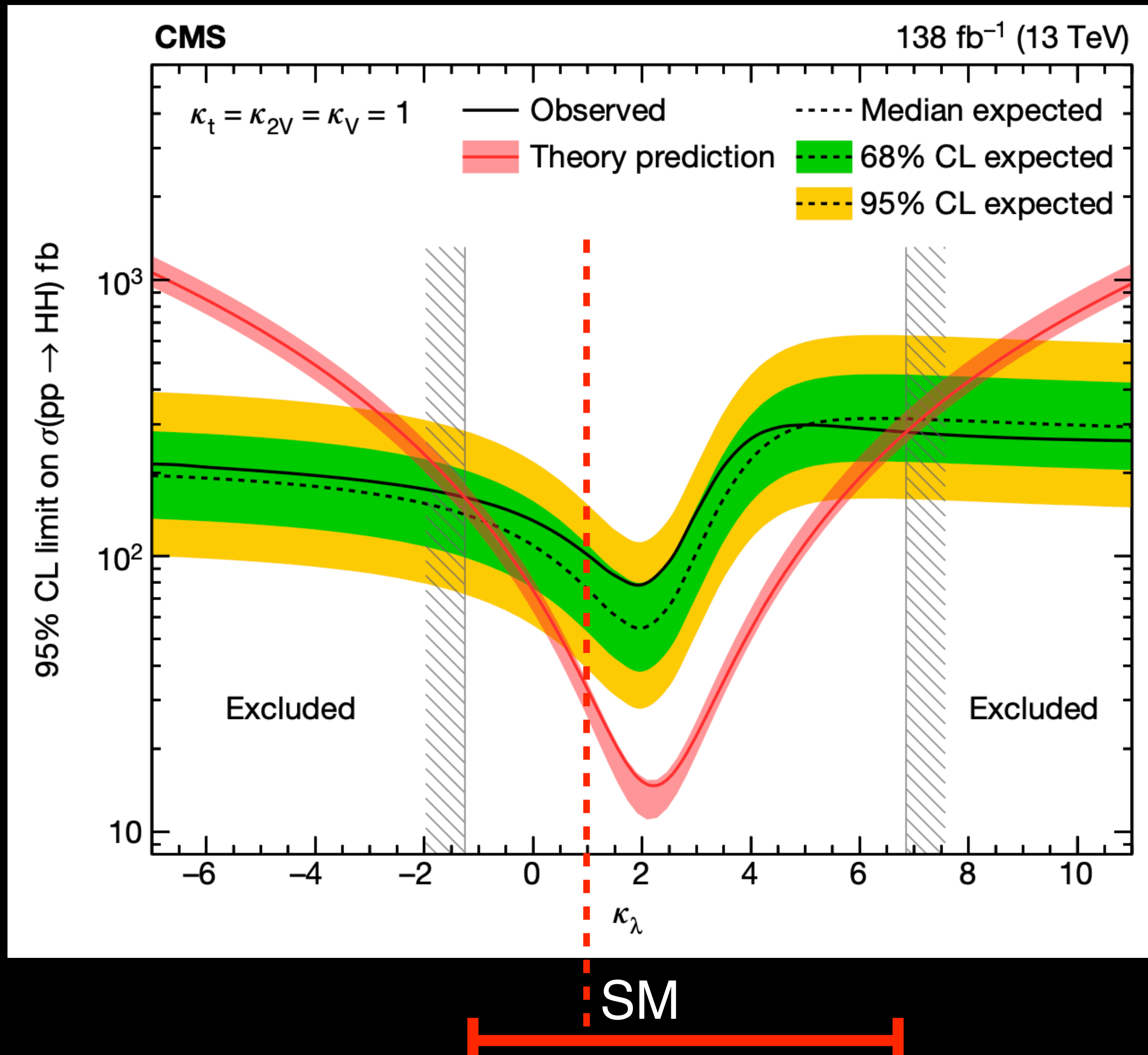
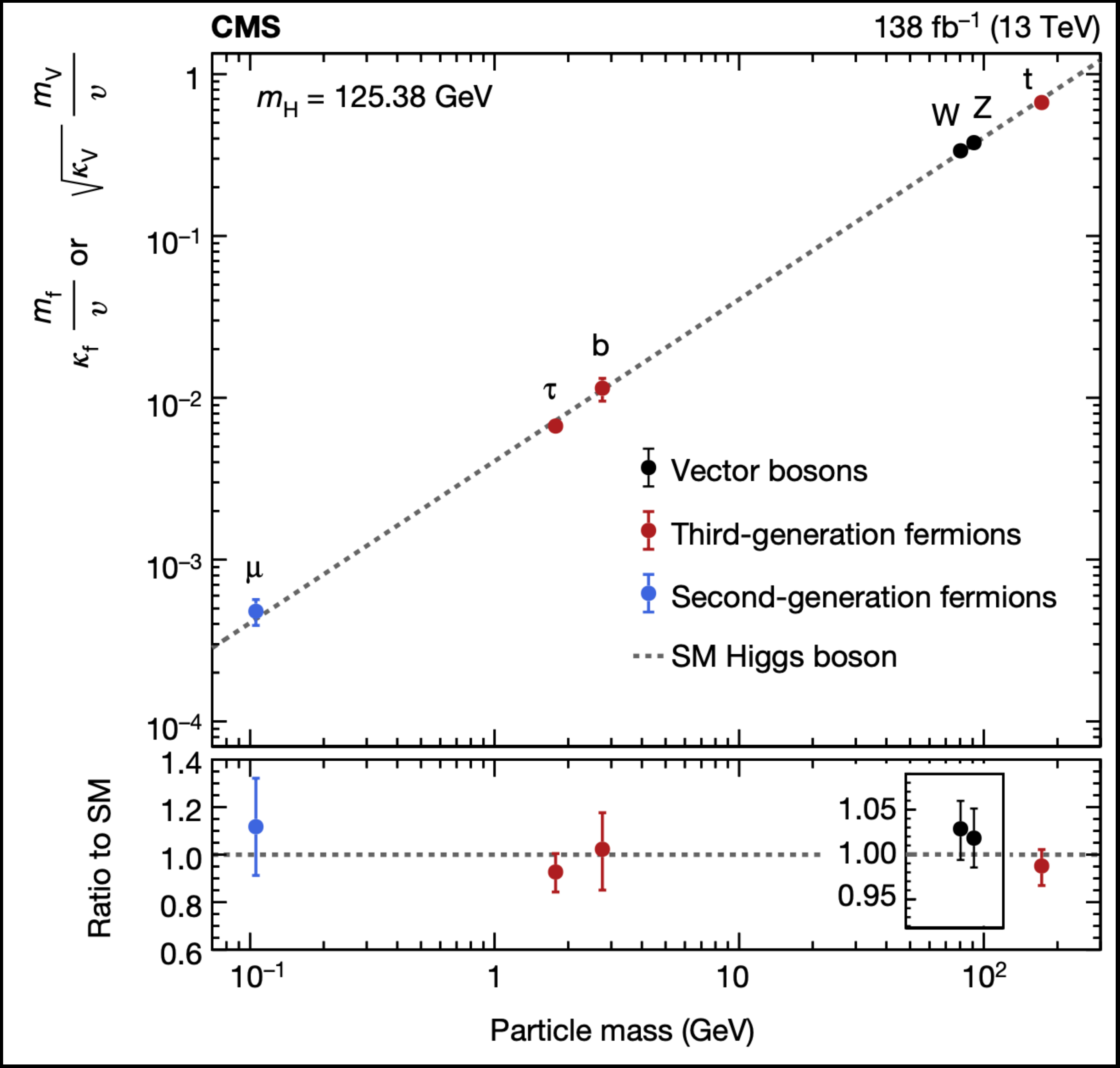
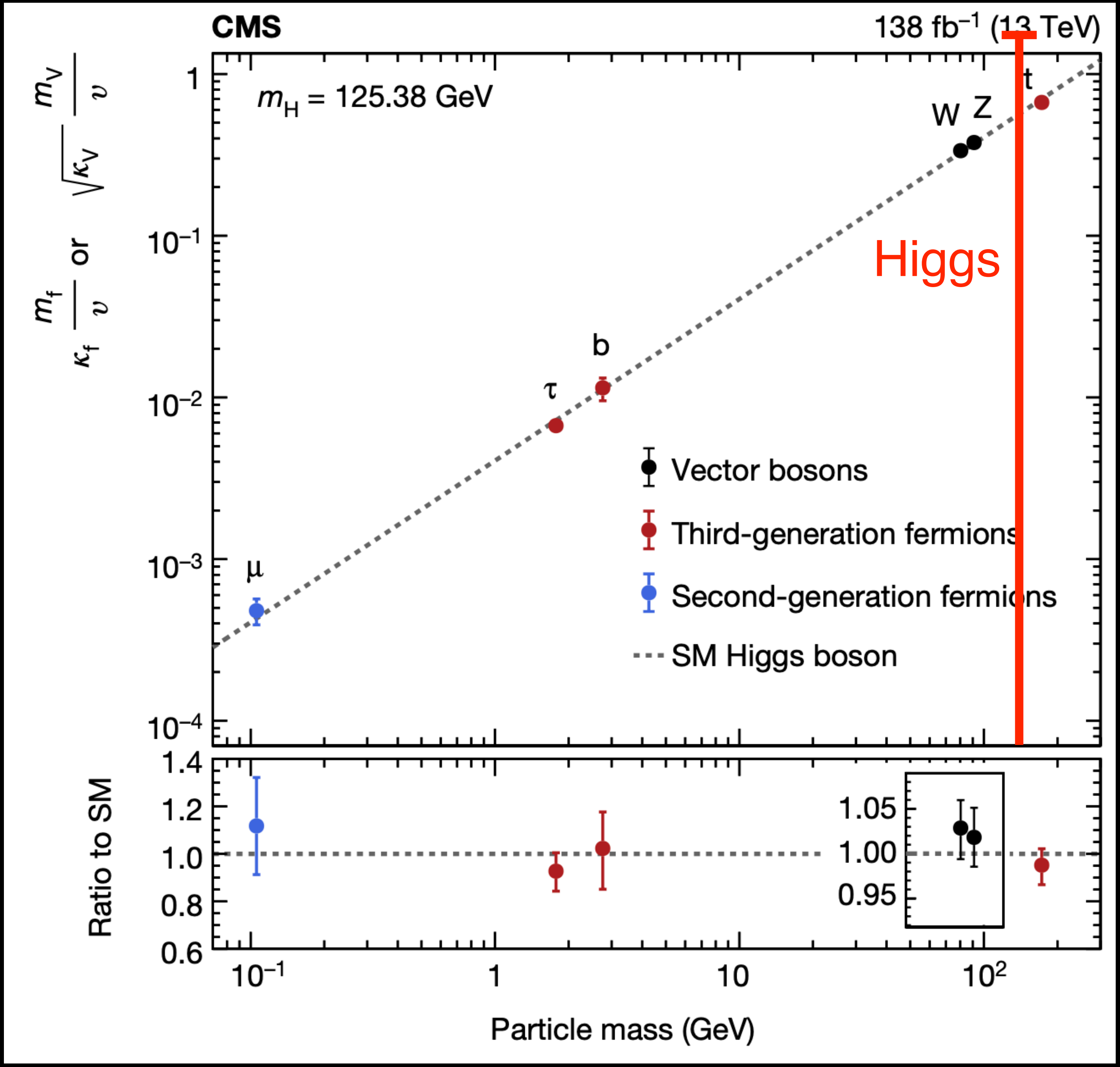


Summary of Higgs couplings



Summary of Higgs couplings



Other (relatively) unprobed couplings

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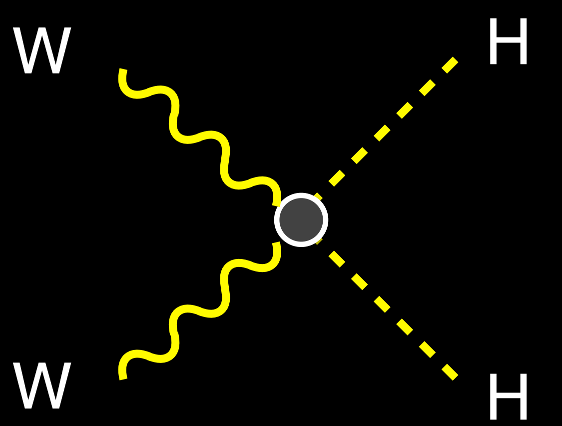

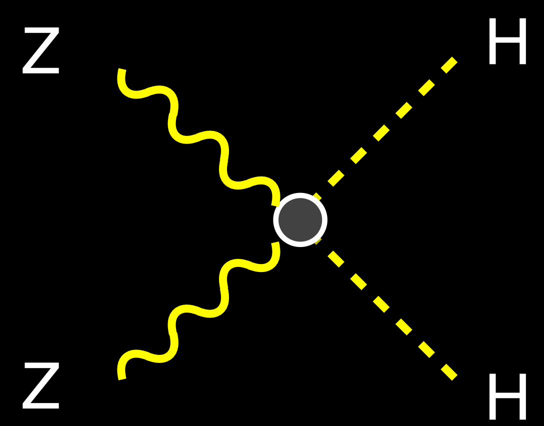

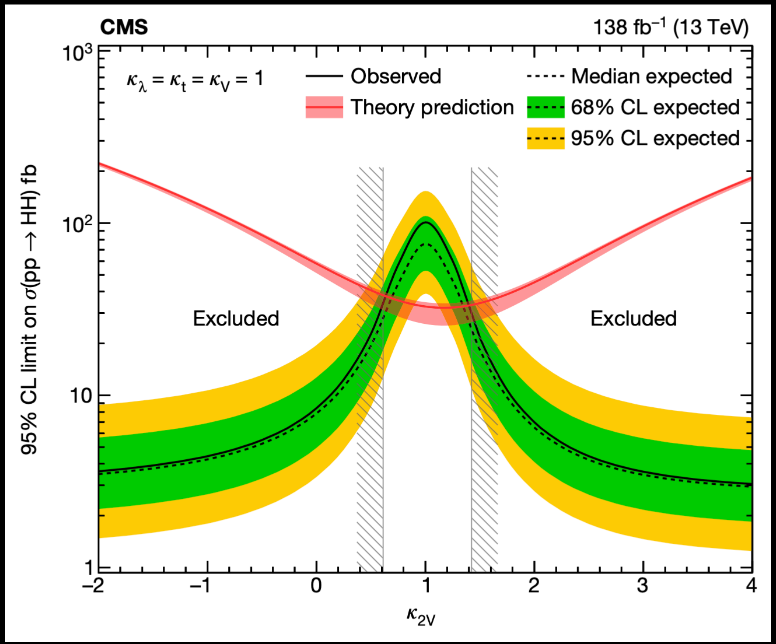

50% error

Other (relatively) unprobed couplings

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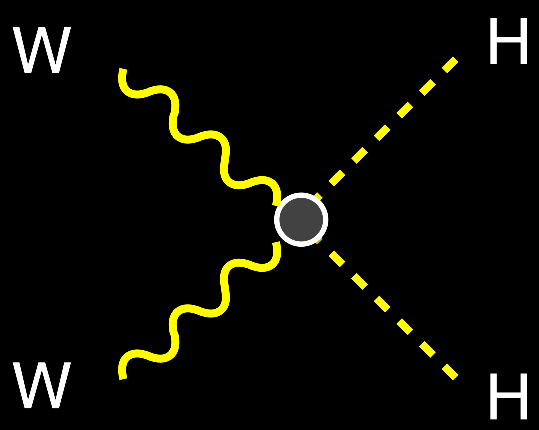
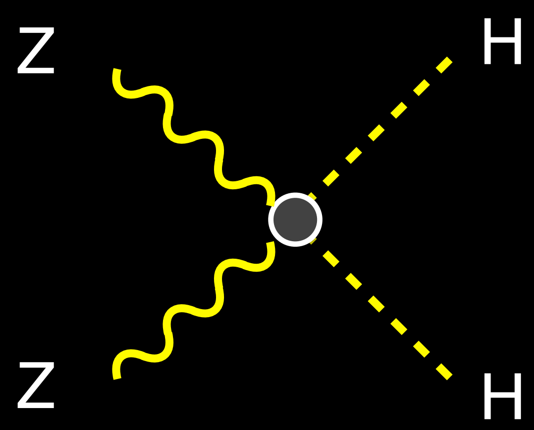
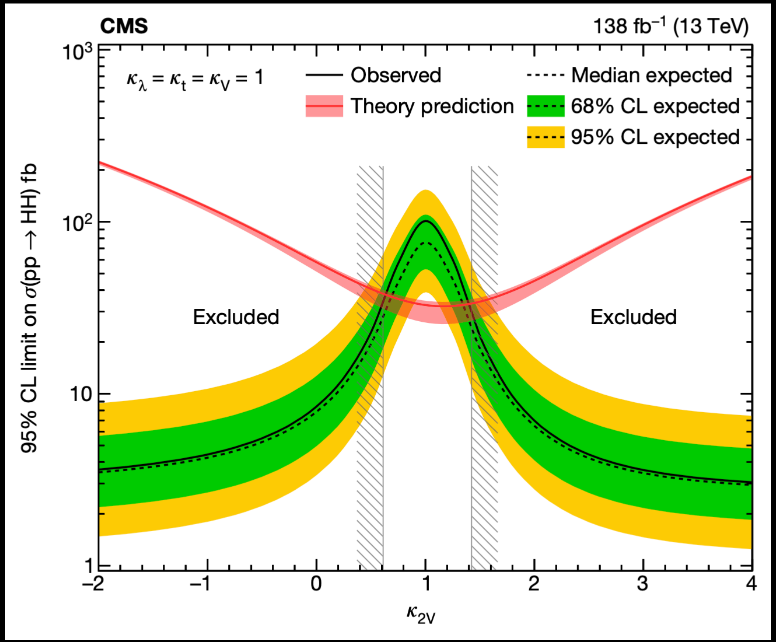
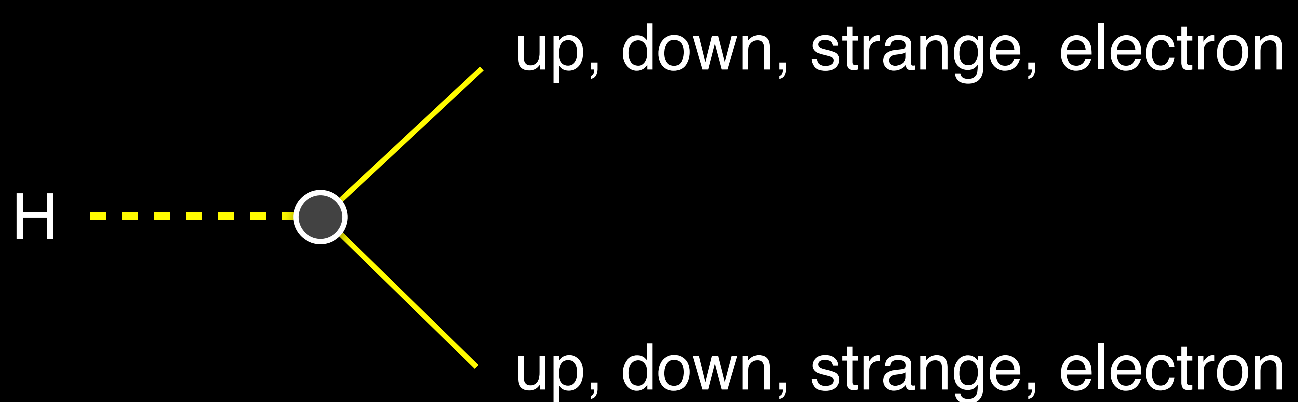






50% error



???

Future Colliders

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

Future Colliders

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Florida

κ-0 fit	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/ eh/hh	$\mu^+\mu^-$
			S2	S2′	250	500	1000	380	1500	3000		240	365		**10000**
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FCC (100km)

muon collider

Future Colliders

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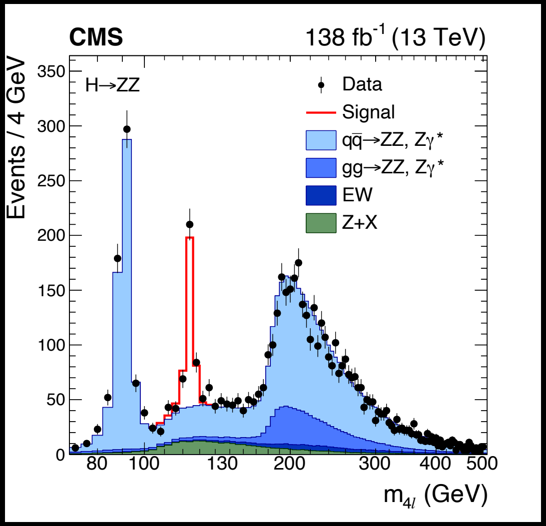
FCC (100km)

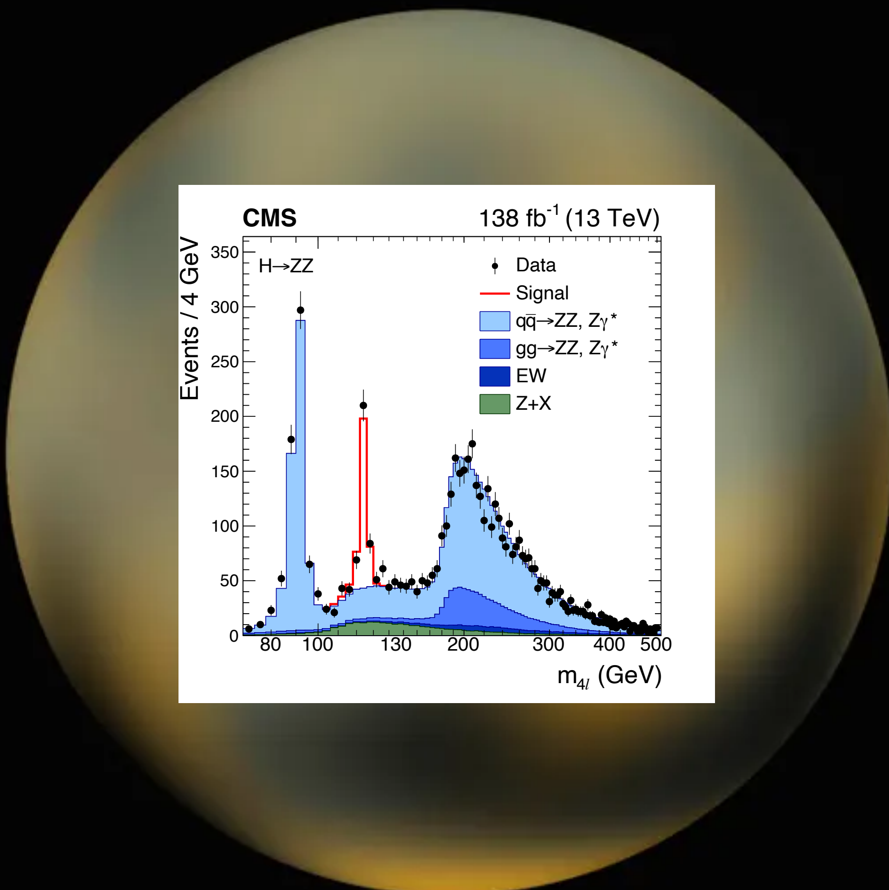
Could be at Fermilab! muon collider

LHC



Current Higgs Portrait

LHC



Current Higgs Portrait

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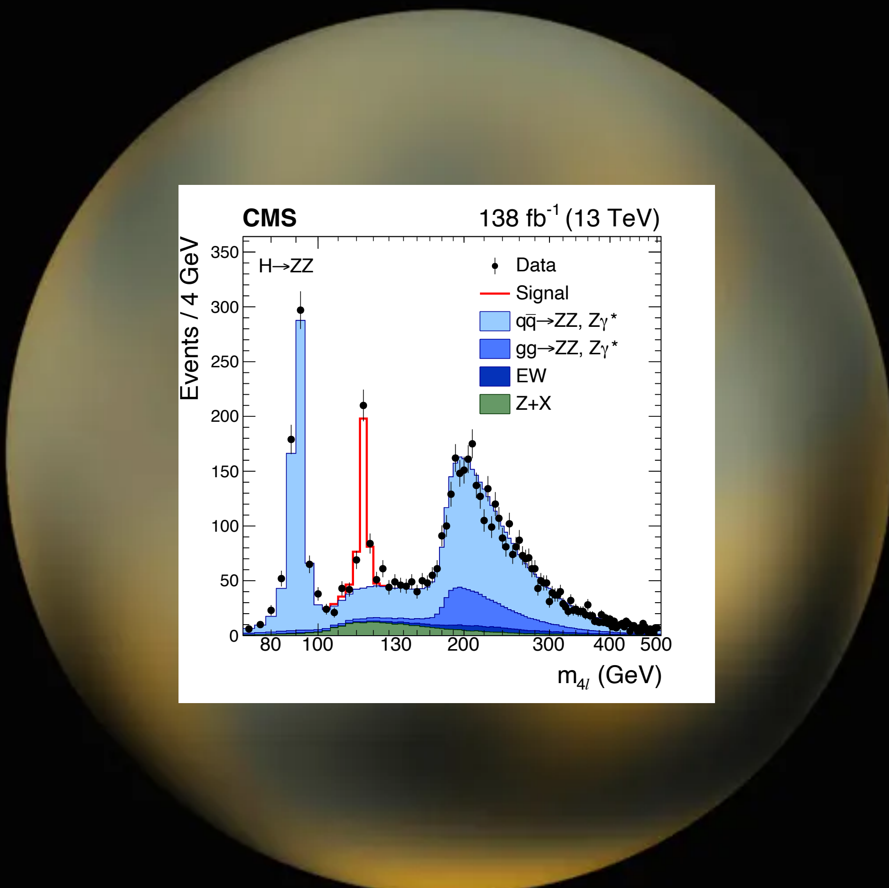
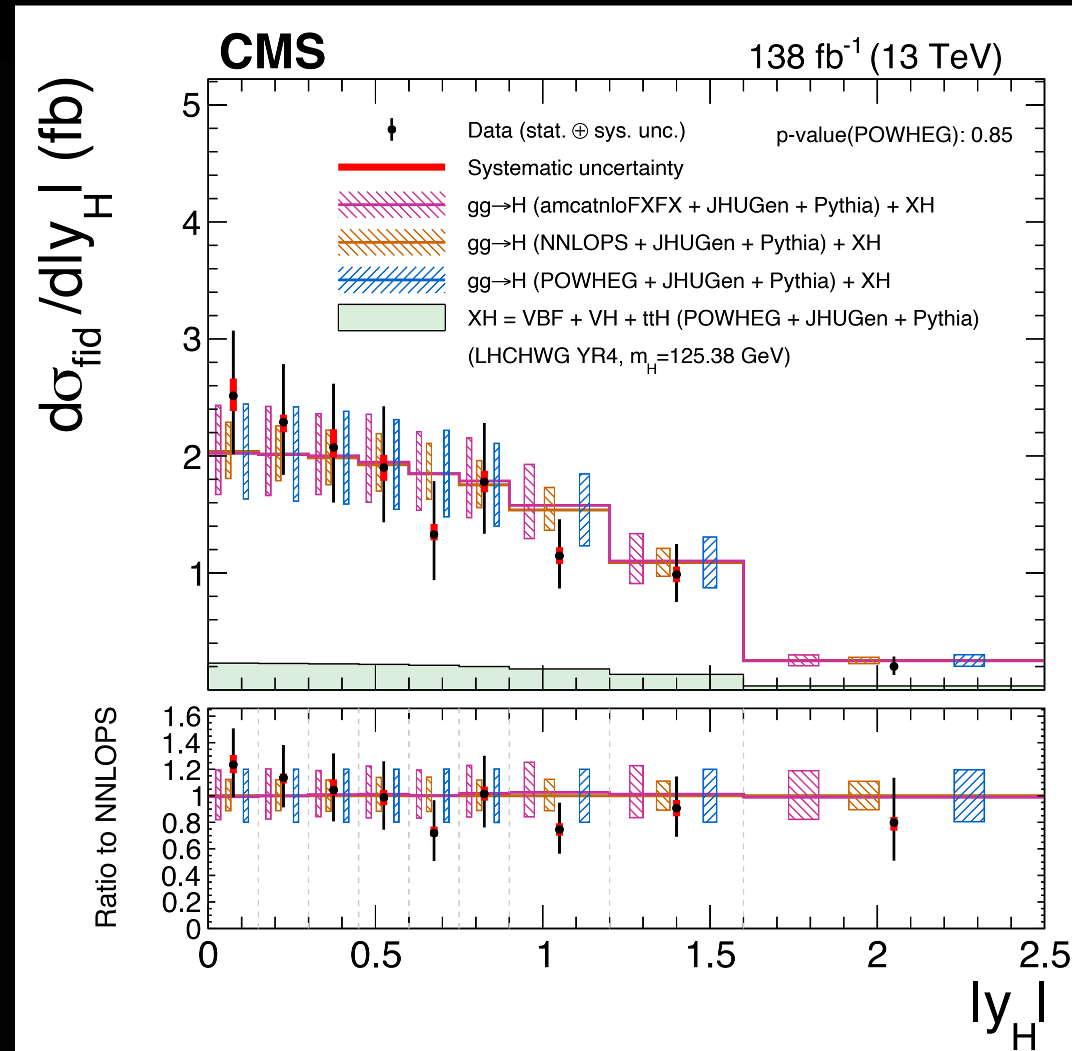
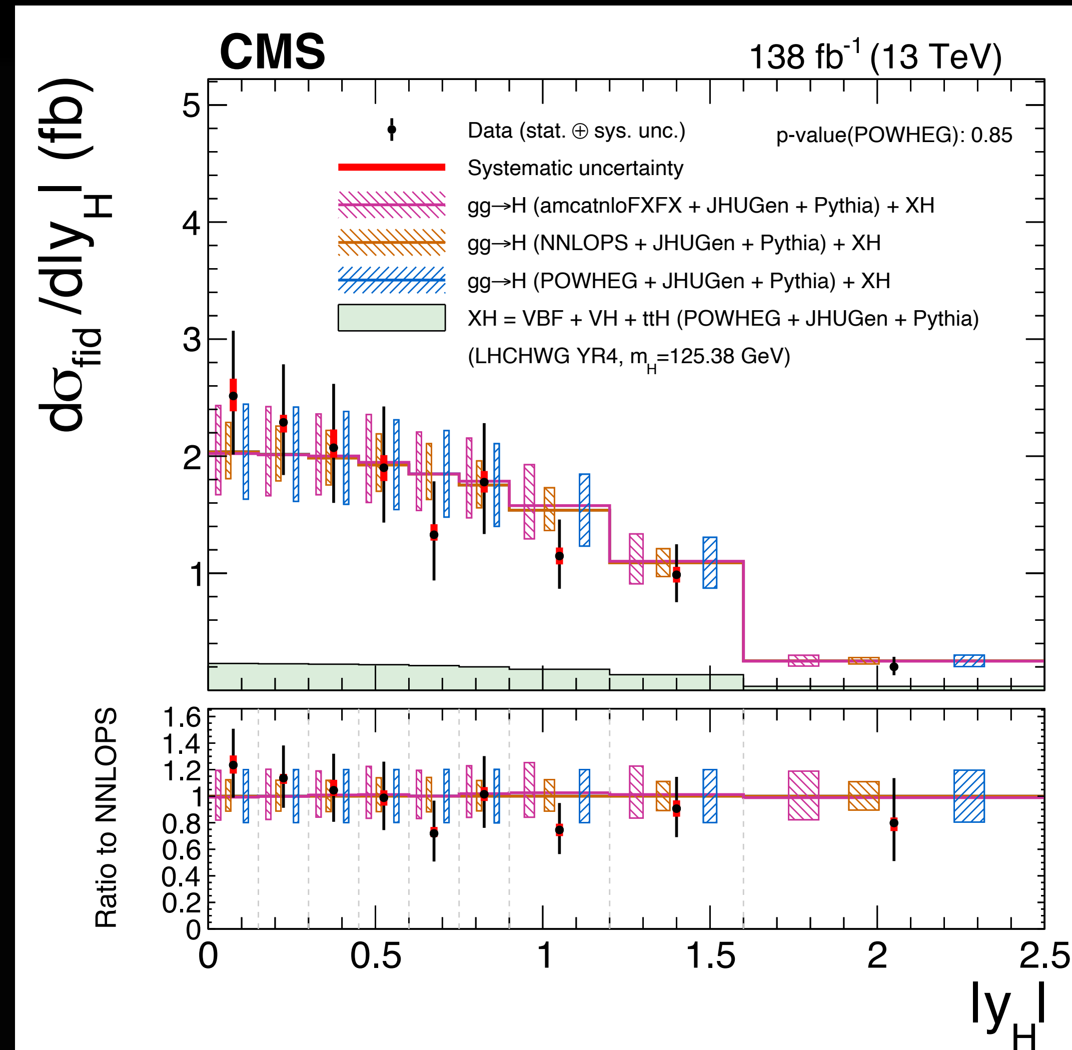
LHC



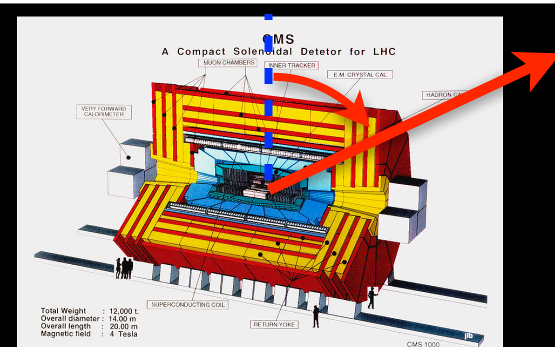


Current Higgs Portrait

LHC



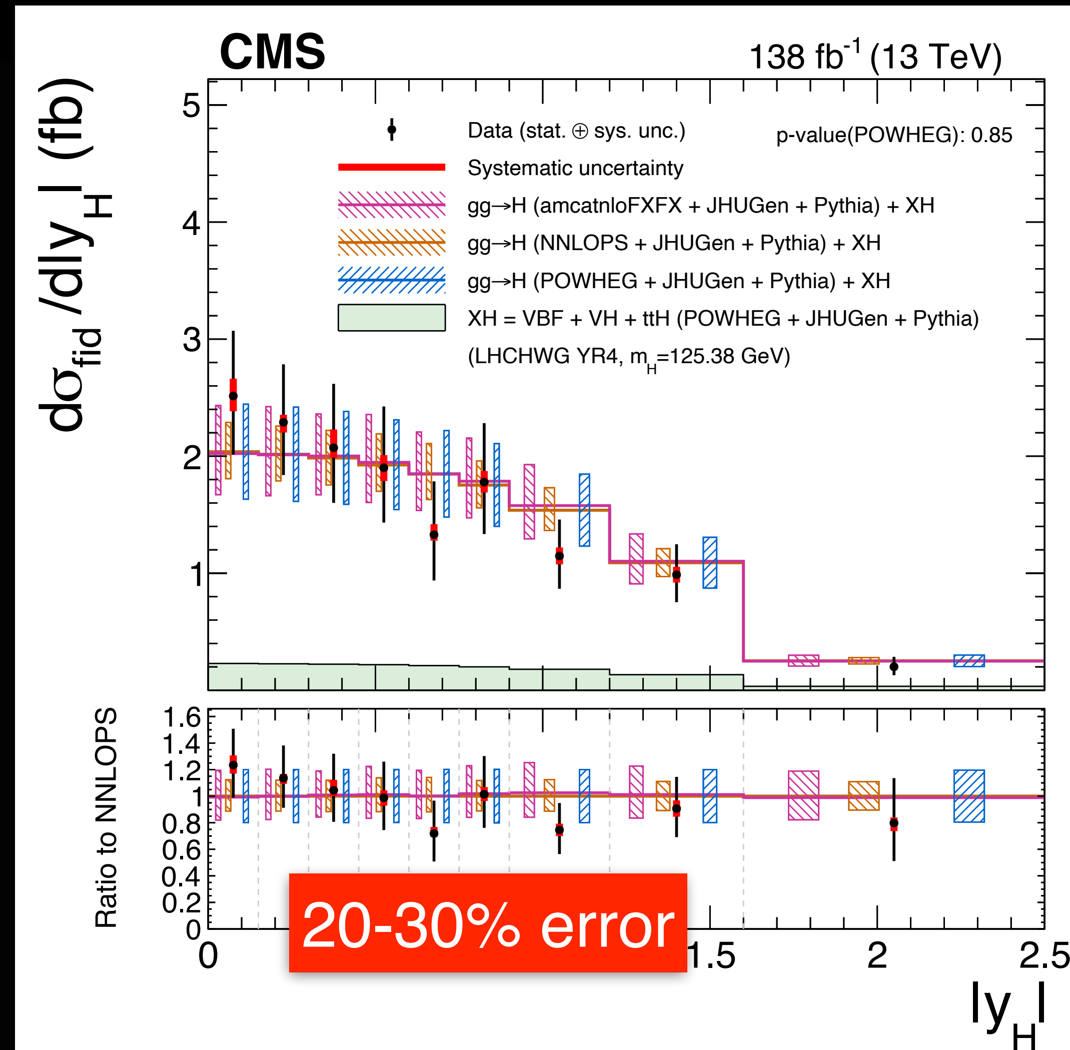
Current Higgs Portrait

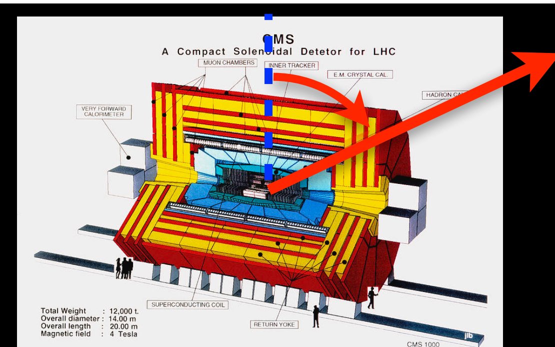


LHC

We know it's "round"

Current Higgs Portrait





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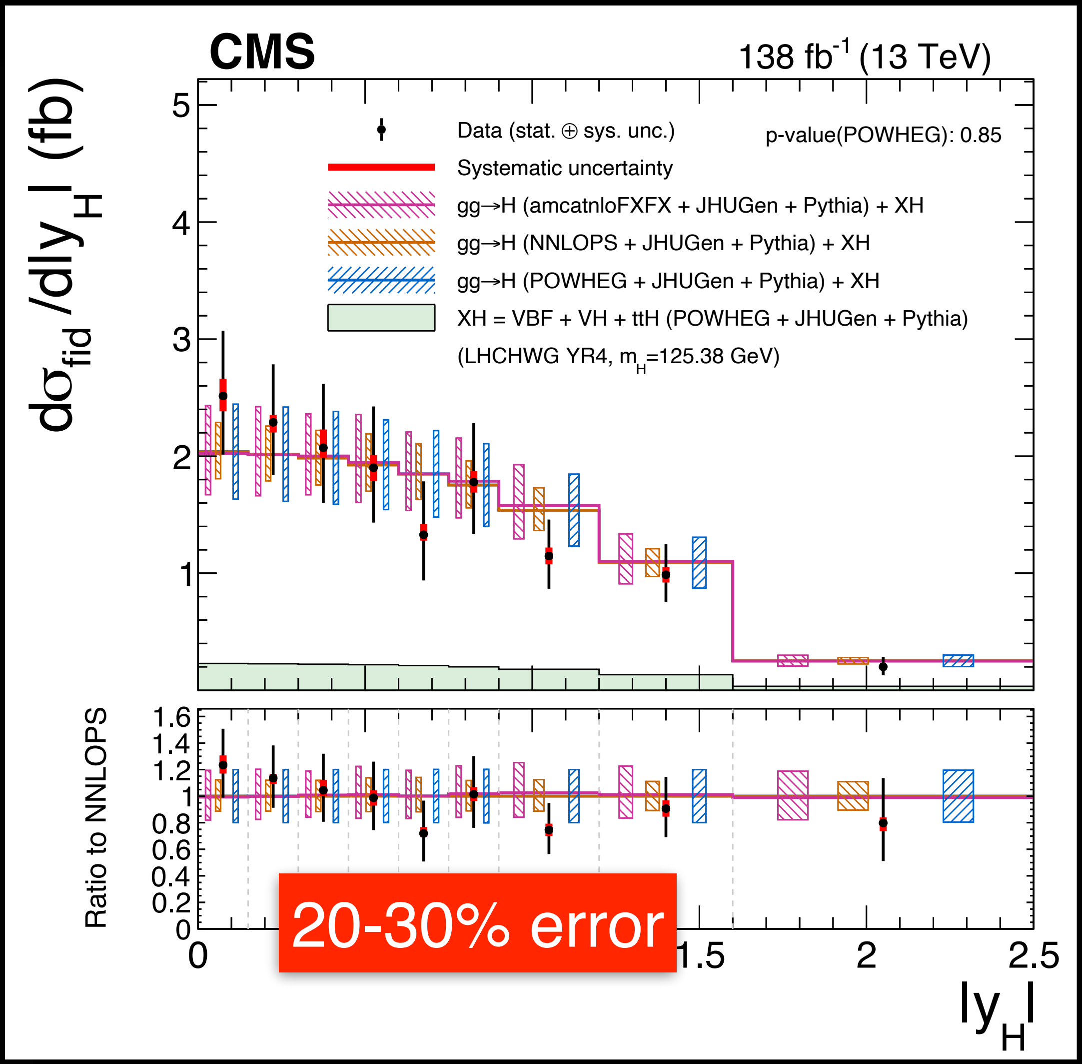
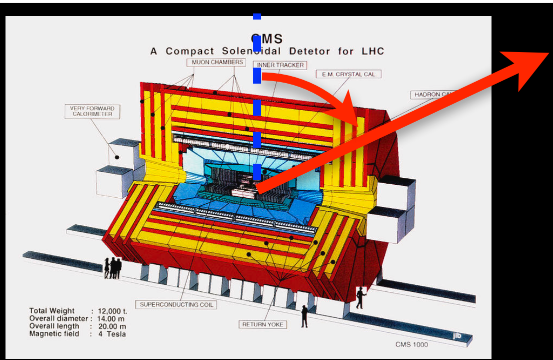
LHC

We know it's "round"

We still can't see the "valleys and mountains"

Current Higgs Portrait





LHC

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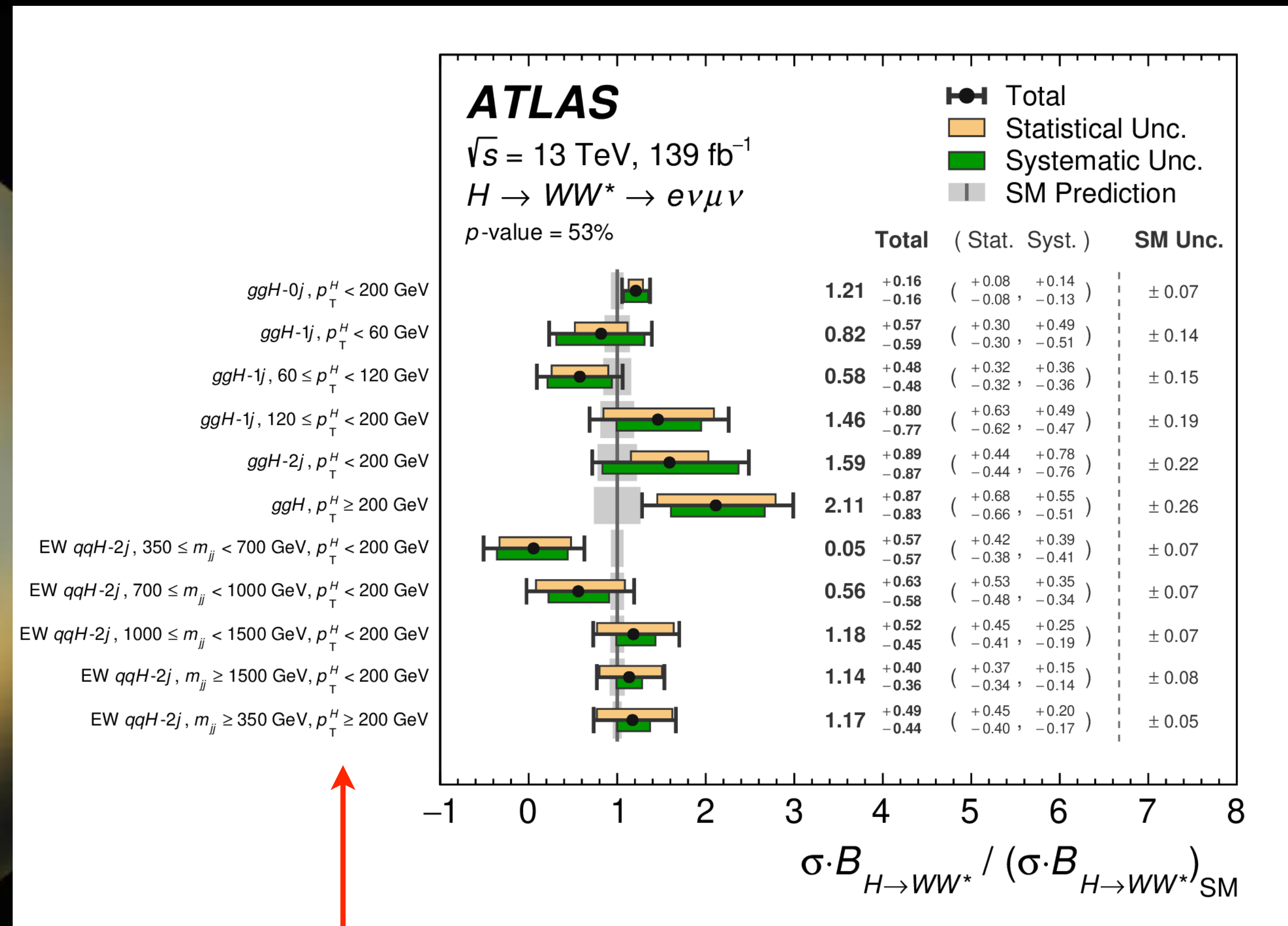
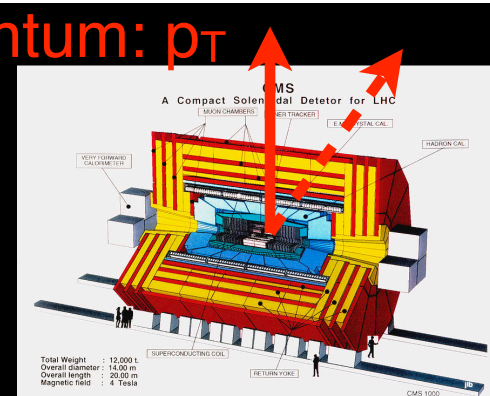


Transverse momentum: p_T



Current Higgs Portrait

LHC

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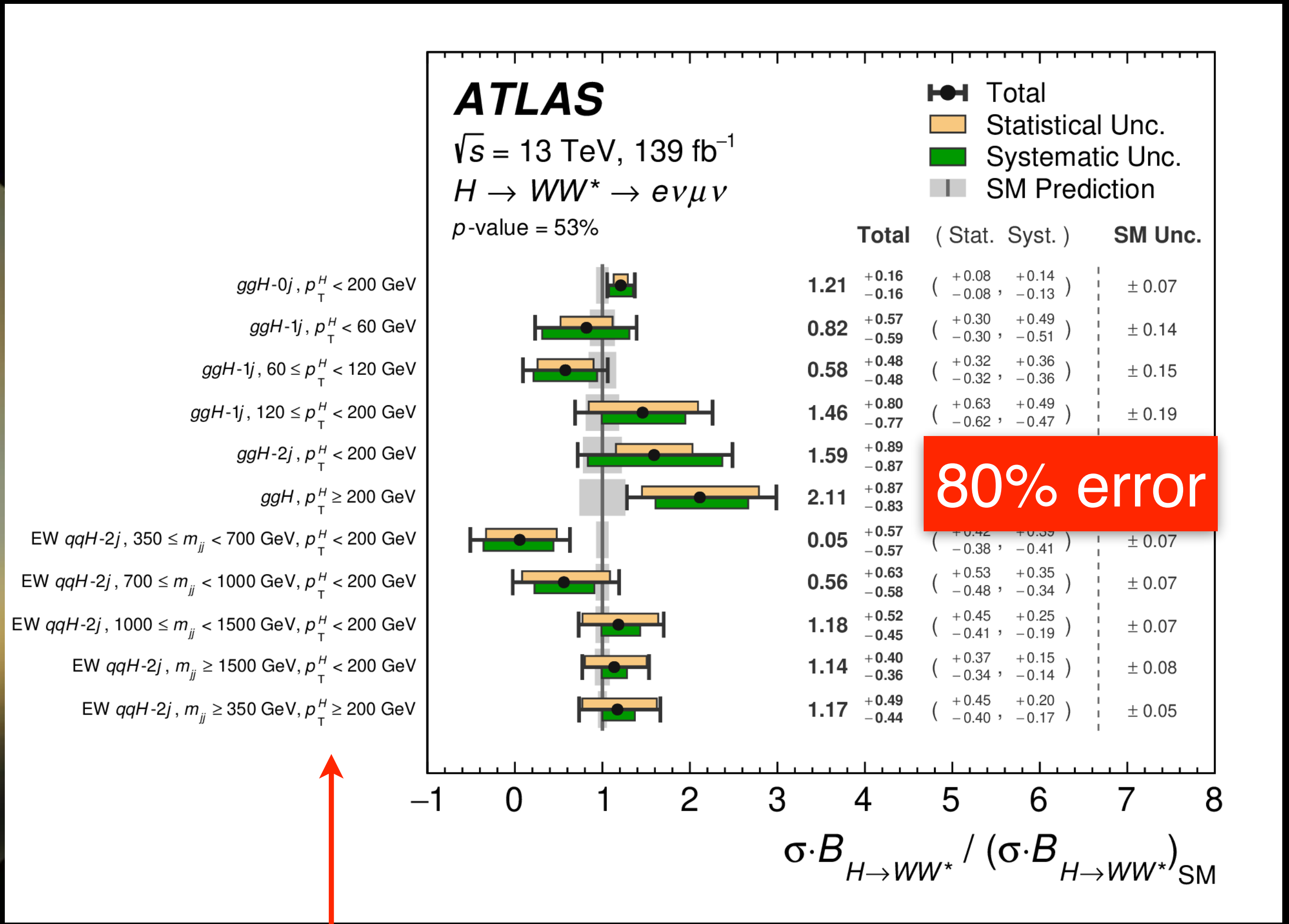
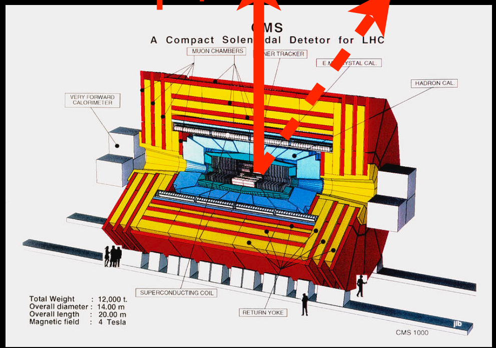


80% error

Transverse momentum: p_T



Current Higgs Portrait

LHC

Current Higgs Portrait

Higgs

Future Colliders

https://www.reddit.com/r/space/comments/3dh5iu/artist_renderings_of_pluto_prior_to_new_horizons/

LHC

New Horizons Flyby of Pluto July 2015

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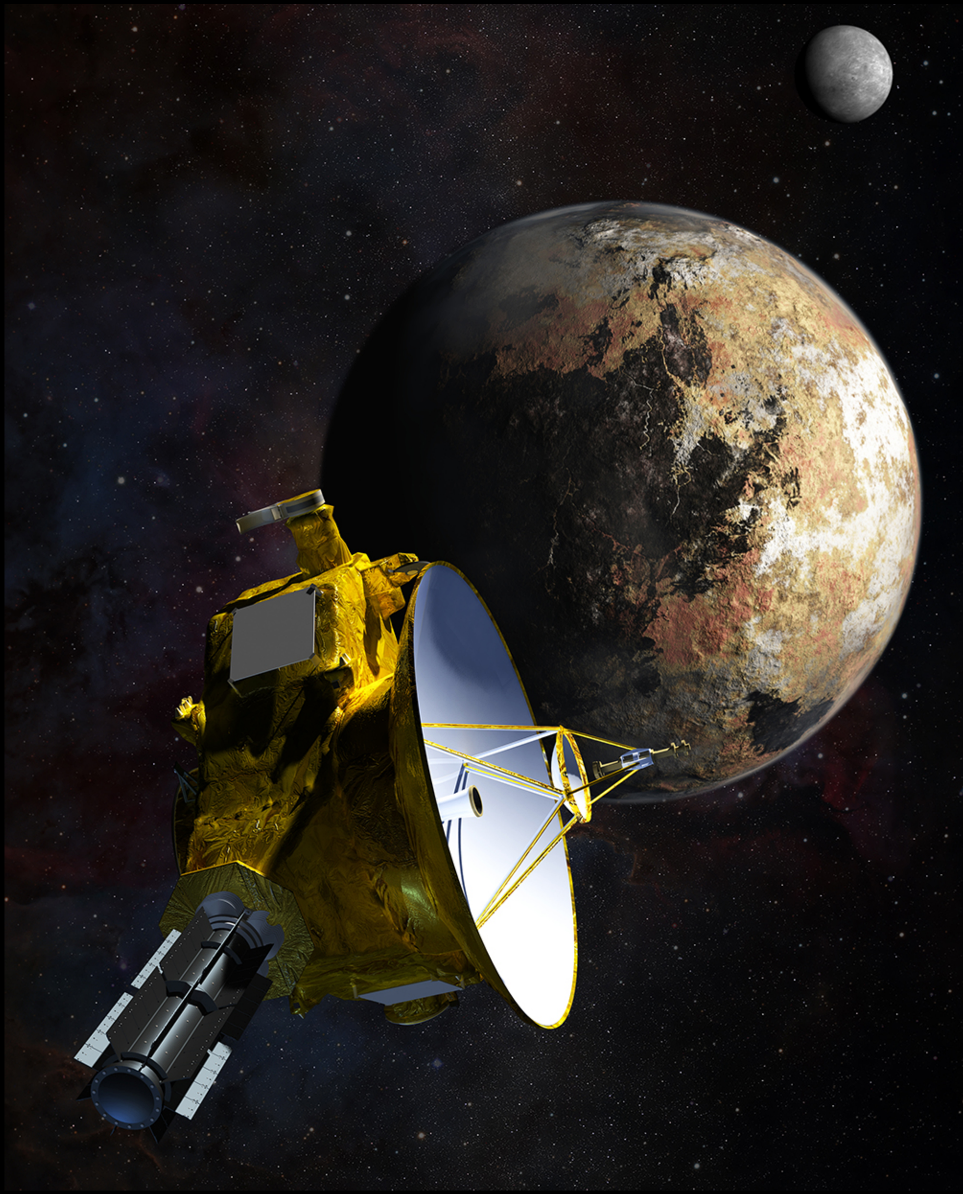
Pluto

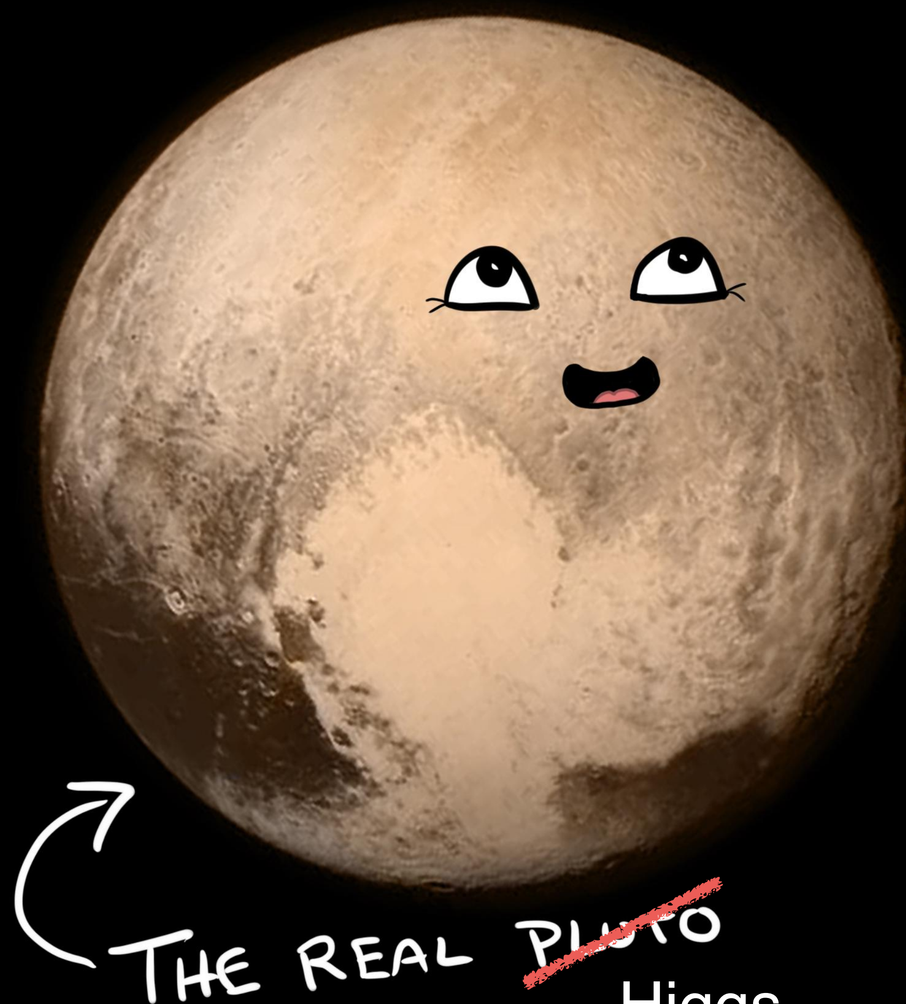
Current Higgs Portrait



LHC

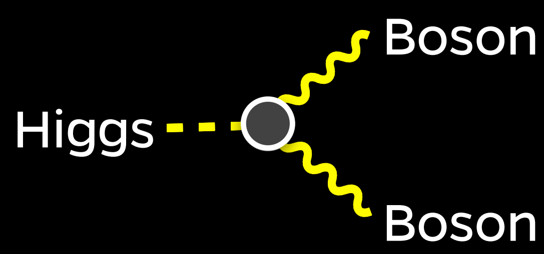
Current Higgs Portrait

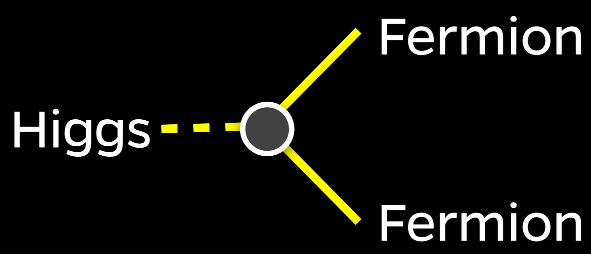
Future Colliders



Higgs

Higgs was needed to explain the SM particle's mass via Higgs to Fermion/Boson couplings





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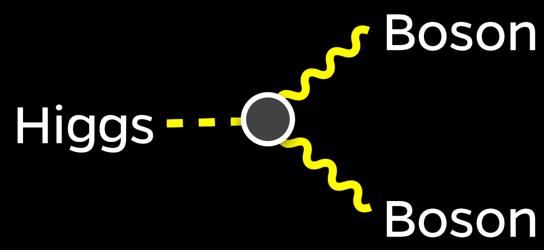
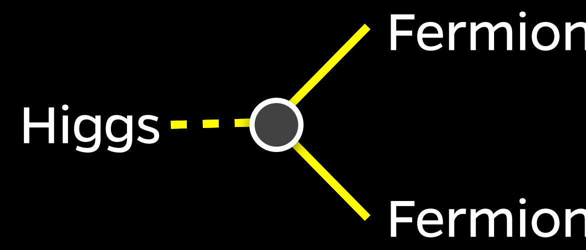
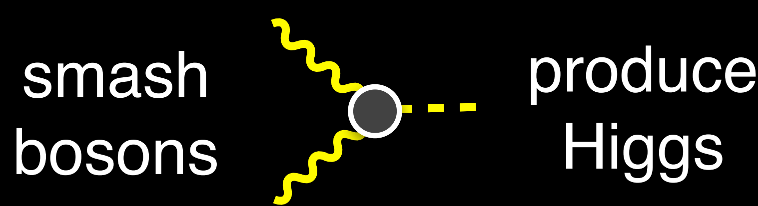
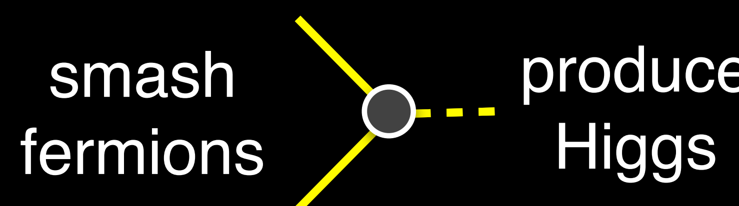




Existence of Higgs field meant we can perturb the Higgs field using SM matters and discover / measure property





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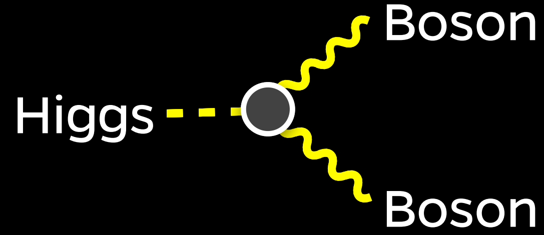

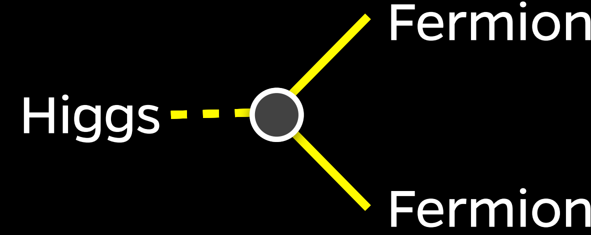

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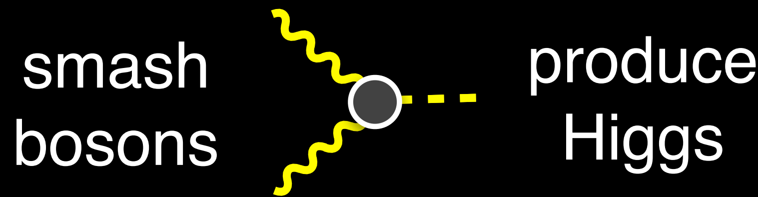
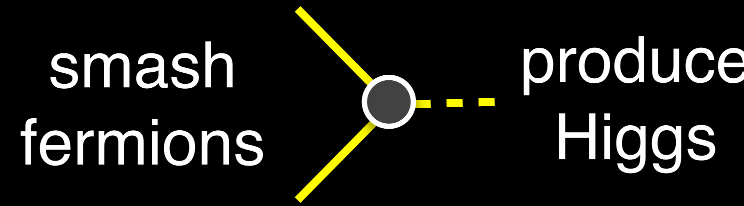
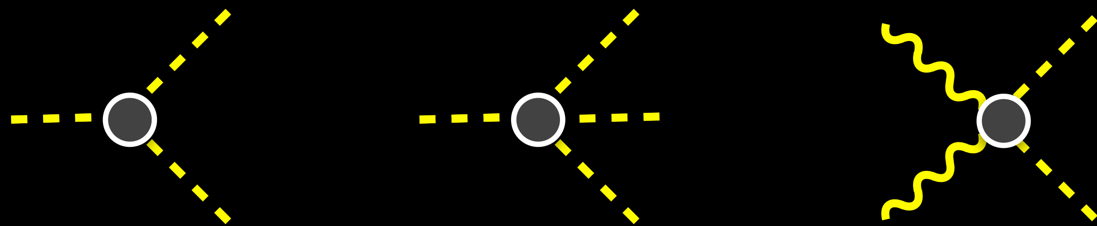




We continue to measure more precisely and also probe much more rare (but important) Higgs couplings, e.g. self-couplings



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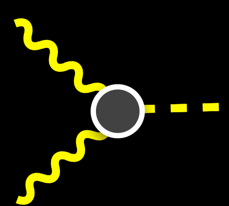
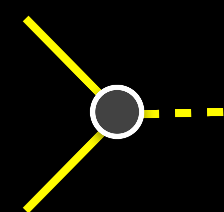
smash bosons



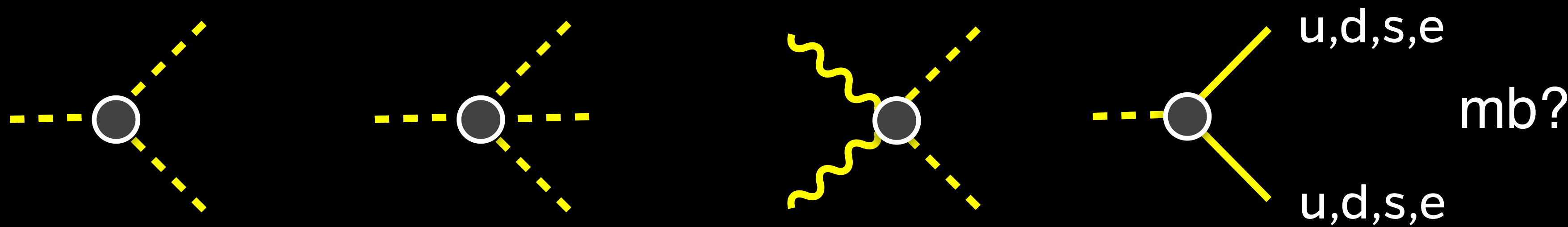
produce Higgs

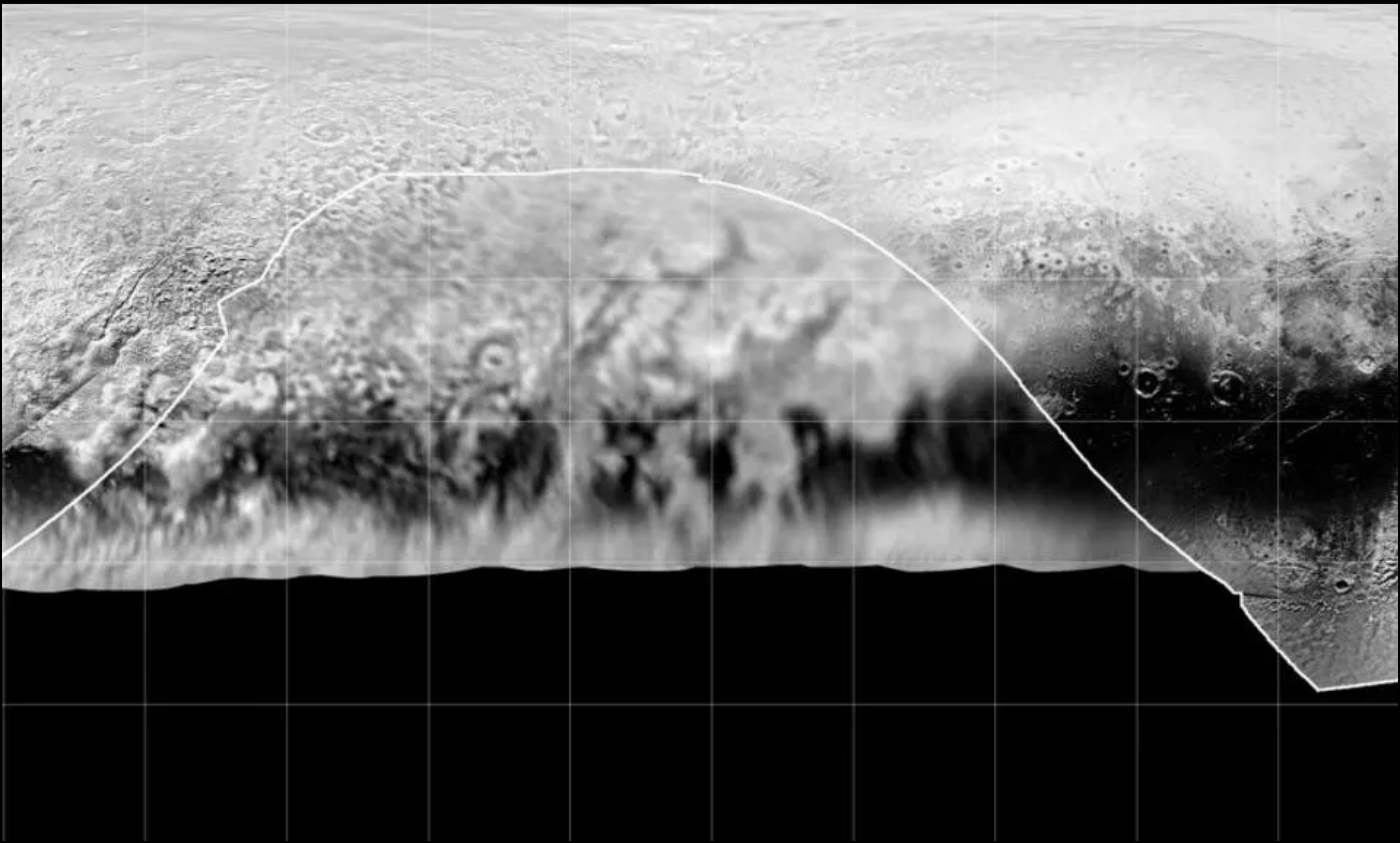
smash fermions

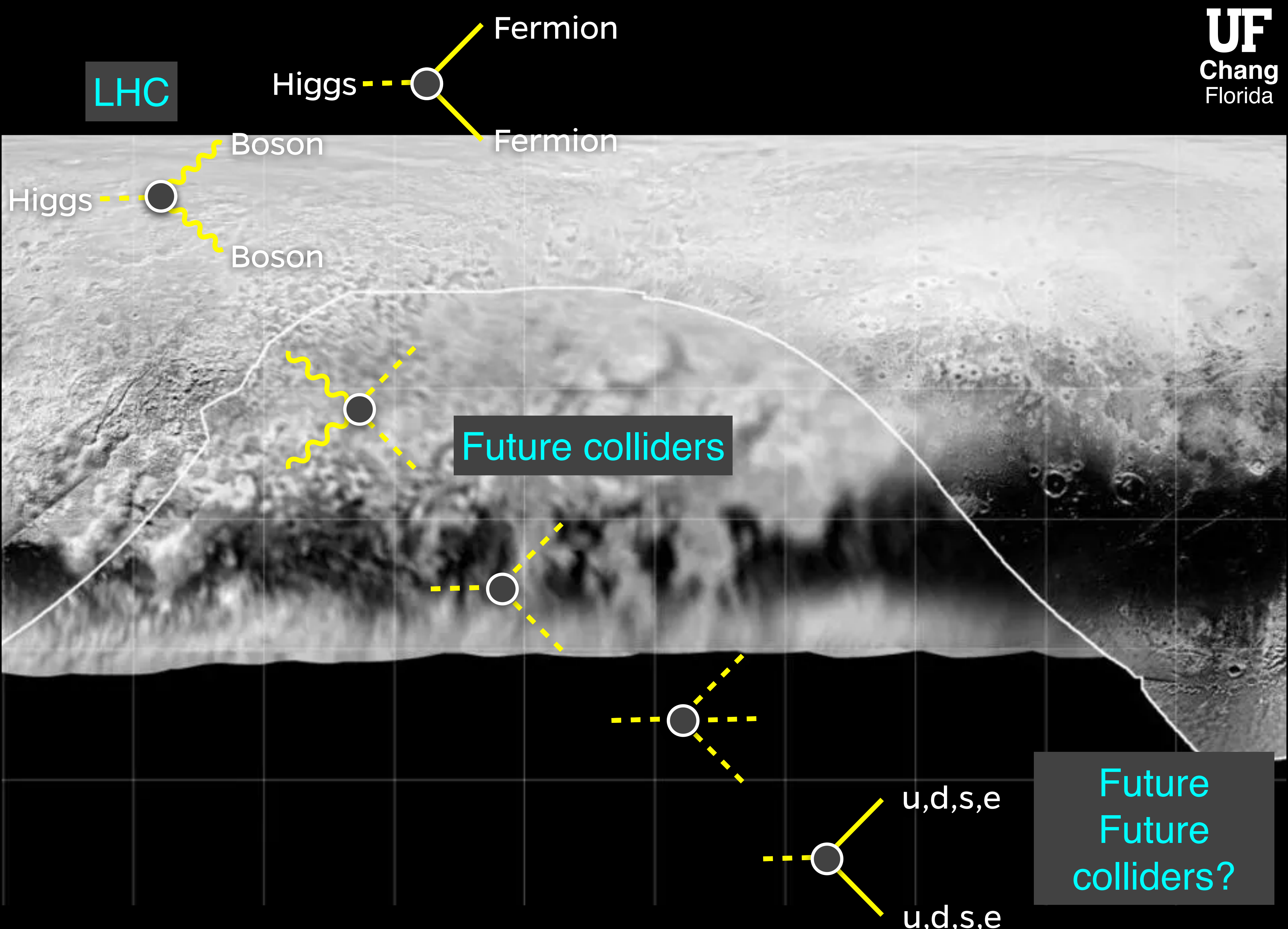


produce Higgs

We continue to measure more precisely and also probe much more rare (but important) Higgs couplings, e.g. self-couplings







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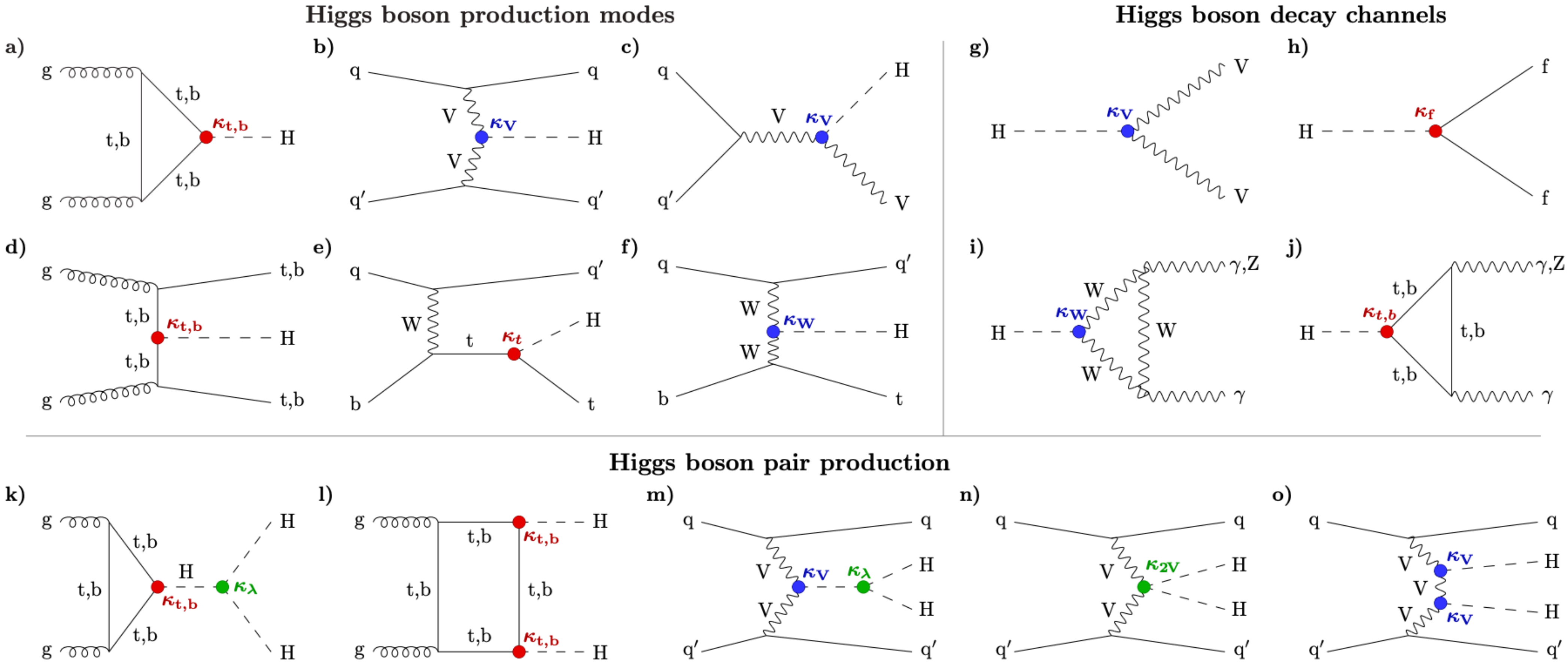


Figure 1: **Feynman diagrams for the leading Higgs boson interactions**

Higgs boson production in (a) gluon-gluon fusion (ggH), (b) vector boson fusion (VBF), (c) associated production with a W or Z (V) boson (VH), (d) associated production with a top or bottom quark pair (ttH or bbH), (e, f) associated production with a single top quark (tH); with Higgs boson decays into (g) heavy vector boson pairs, (h) fermion-antifermion pairs, and (i, j) photon pairs or $Z\gamma$; Higgs boson pair production: (k, l) via gluon-gluon fusion, and (m, n, o) via vector boson fusion. The different Higgs boson interactions are labelled with the coupling modifiers κ, and highlighted in different colours for Higgs-fermion interactions (red), Higgs-gauge-boson interactions (blue), and multiple Higgs boson interactions (green). The distinction between a particle and its antiparticle is dropped.

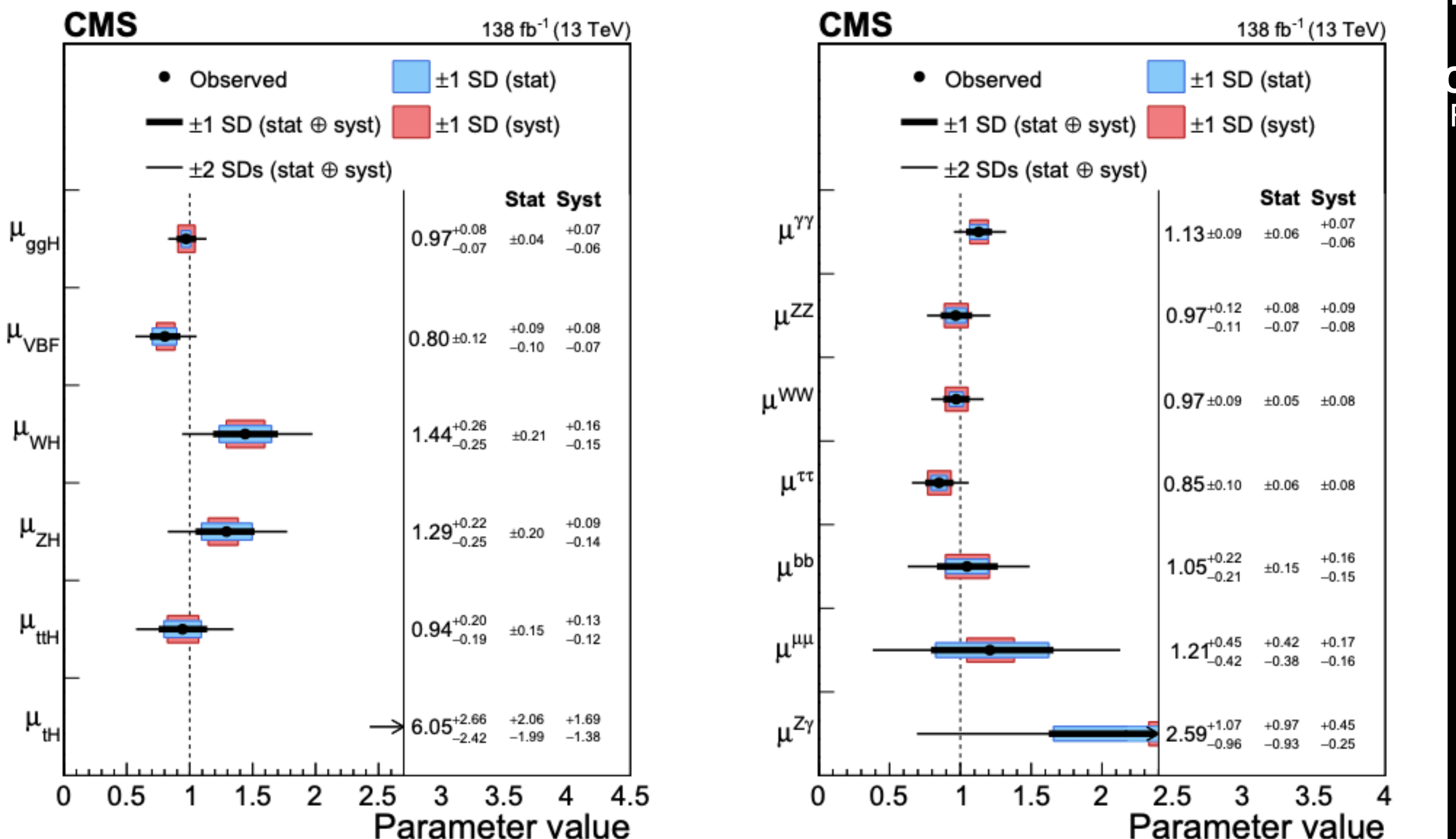


Figure 2: **The agreement with the SM predictions for production modes and decay channels.** Signal strength parameters extracted for (left) various production modes μ_i, assuming $\mathcal{B}^f = (\mathcal{B}^f)_{SM}$, and (right) decay channels μ^f, assuming $\sigma_i = (\sigma_i)_{SM}$. The thick (thin) black lines indicate the 1 (2) s.d. confidence intervals, with the systematic and statistical components of the 1 s.d. interval indicated by the red and blue bands, respectively. The vertical dashed line at unity represents the values of μ_i and μ^f in the SM. The covariance matrices of the fitted signal strength parameters are shown in Extended Data Fig. B.5. The *p*-value with respect to the SM prediction are 3.1% and 30.1% for the left and right plot, respectively. The *p*-value corresponds to the probability that a result deviates as much, or more, from the SM prediction as the observed one.

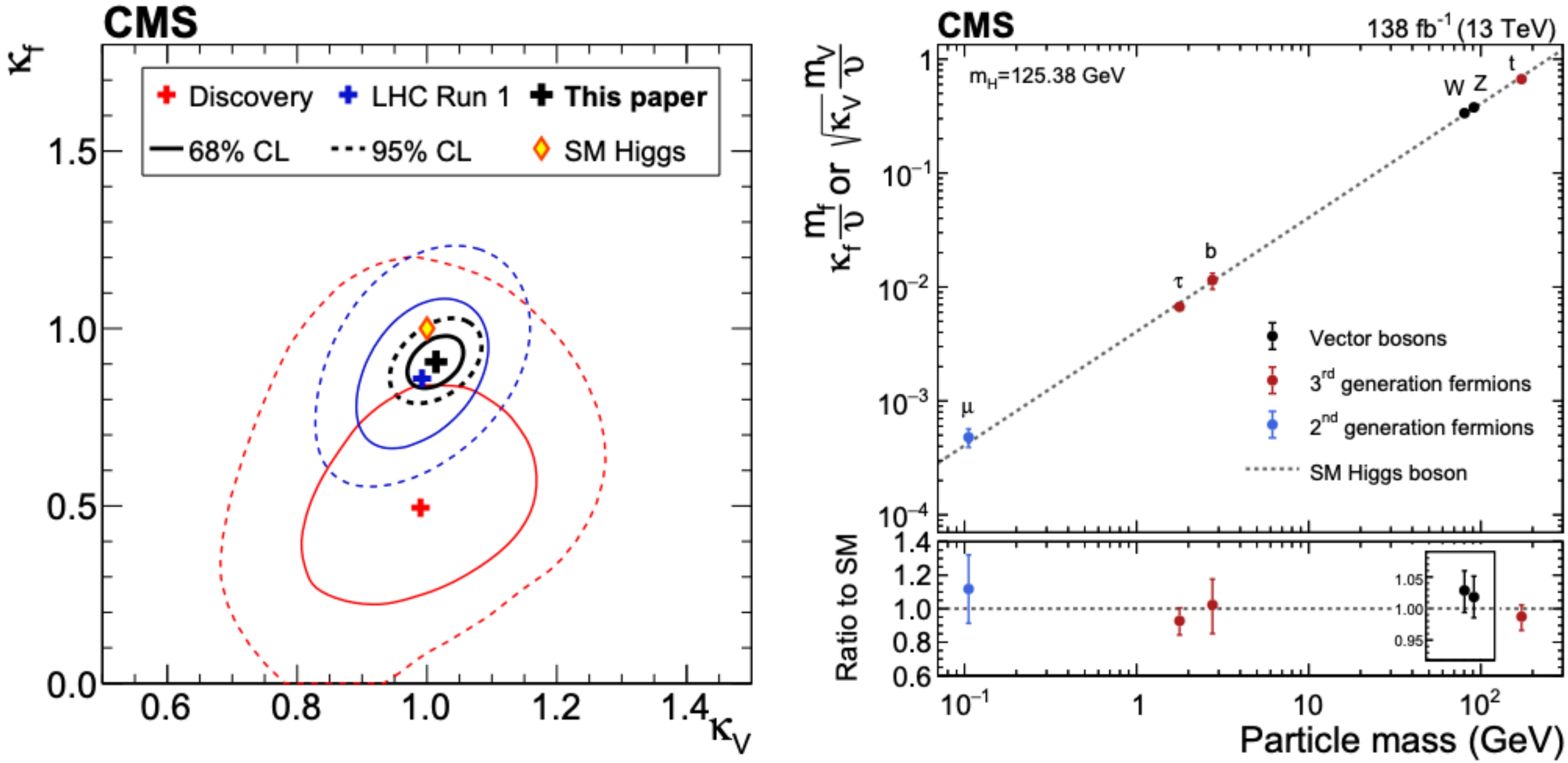


Figure 3: **A portrait of the Higgs boson couplings to fermions and vector bosons.**
(left) Constraints on the Higgs boson coupling modifiers to fermions (κ_f) and heavy gauge bosons (κ_V), in different data sets: discovery (red), the full LHC Run 1 (blue), and the data presented here (black). The SM prediction corresponds to $\kappa_V = \kappa_f = 1$ (diamond marker). (right) The measured coupling modifiers of the Higgs boson to fermions and heavy gauge bosons, as functions of fermion or gauge boson mass, where υ is the vacuum expectation value of the BEH field (cf. Methods section A.7). For gauge bosons, the square root of the coupling modifier is plotted, to keep a linear proportionality to the mass, as predicted in the SM. The p-value with respect to the SM prediction for the right plot is 37.5%.

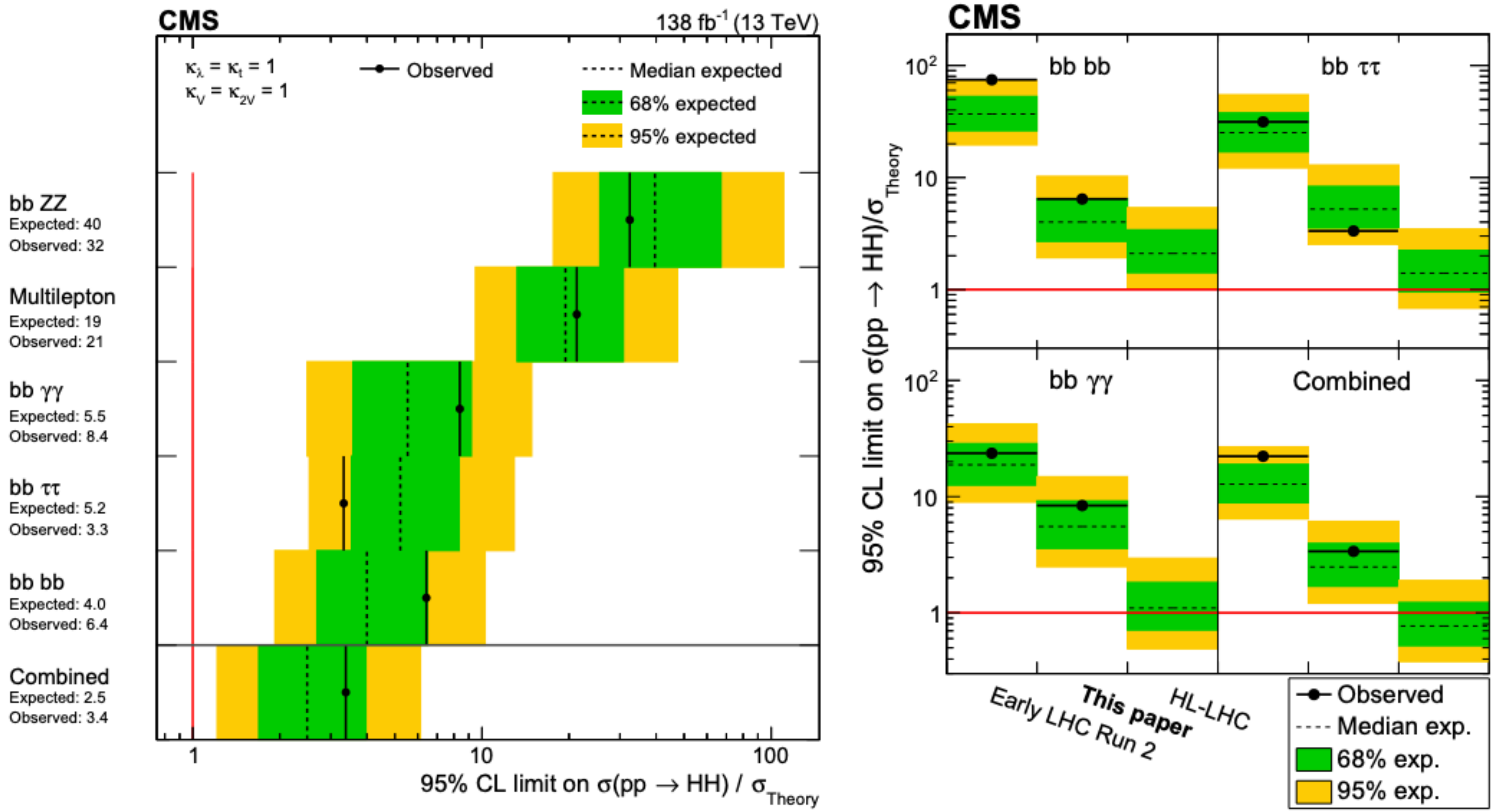
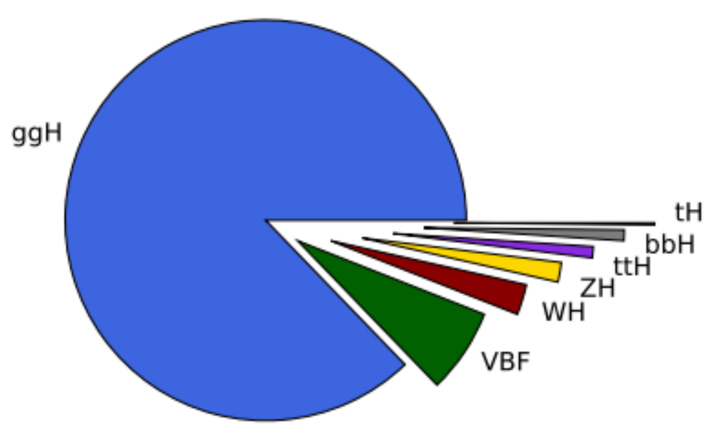
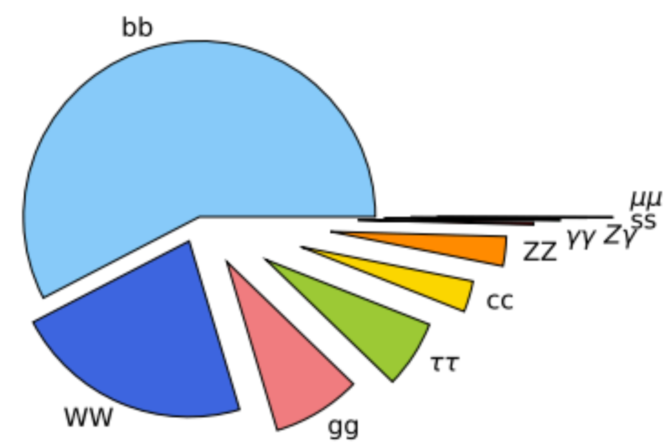


Figure 5: **Limits on the production of Higgs boson pairs and their time evolution.** (left) The expected and observed limits on the ratio of experimentally estimated production cross section and the expectation from the SM (σ_{Theory}) in searches using different final states and their combination. The search modes are ordered, from upper to lower, by their expected sensitivities from the least to the most sensitive. The overall combination of all searches is shown by the lowest entry. (right) Expected and observed limits on HH production in different data sets: early LHC Run 2 data (35.9 fb^{-1}), present results using full LHC Run 2 data (138 fb^{-1}), and projections for the HL-LHC (3000 fb^{-1}).

Table B.1: **The SM Higgs production cross sections and branching fractions.** Theoretical cross sections for each production mode and branching fractions for the decay channels, at $\sqrt{s} = 13$ TeV and for $m_{\mathrm{H}} = 125.38$ GeV [39].

Production mode	Cross section (pb)	Decay channel	Branching fraction (%)
ggH	48.31 ± 2.44	bb	57.63 ± 0.70
VBF	3.771 ± 0.807	WW	22.00 ± 0.33
WH	1.359 ± 0.028	gg	8.15 ± 0.42
ZH	0.877 ± 0.036	$\tau\tau$	6.21 ± 0.09
ttH	0.503 ± 0.035	cc	2.86 ± 0.09
bbH	0.482 ± 0.097	ZZ	2.71 ± 0.04
tH	0.092 ± 0.008	$\gamma\gamma$	0.227 ± 0.005
		$Z\gamma$	0.157 ± 0.009
		ss	0.025 ± 0.001
		$\mu\mu$	0.0216 ± 0.0004





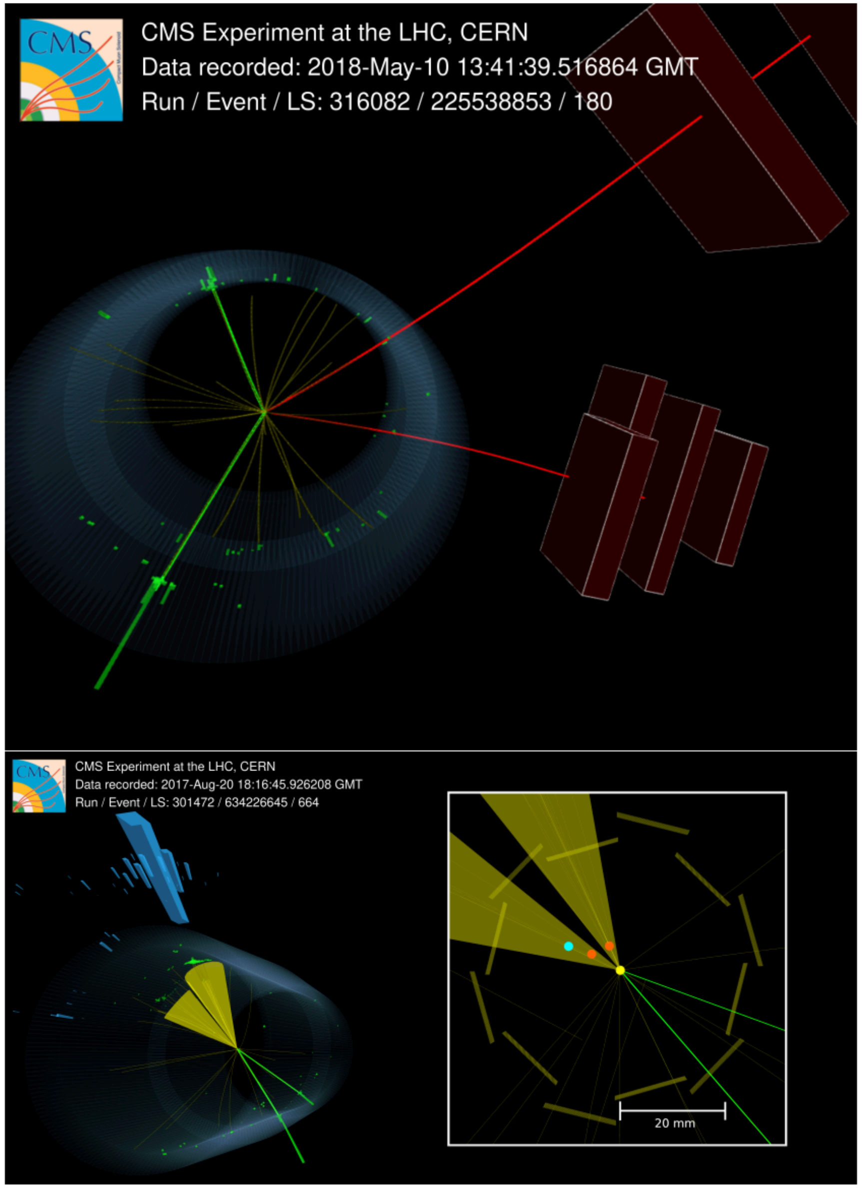


Figure B.2: **Higgs boson candidate events.**
(upper) An event display of a candidate $H \to ZZ \to ee\mu\mu$. (lower) An event display of an $H \to bb$ candidate produced in association with a Z boson decaying into an electron-positron pair, in pp collisions at $\sqrt{s} = 13$ TeV recorded by CMS. The charged-particle tracks, as reconstructed in the inner tracker, are shown in yellow; the electrons are shown in green, the energy deposited by the electrons in the ECAL is shown as large green towers, the size of which is proportional of the amount of energy deposited; the blue towers are indicative of the energy deposits in the HCAL, while the red boxes are the muon chambers crossed by the muons (red tracks); the yellow cones represent the reconstructed jets. (lower, inset) The zoom into the collision region shows the displaced secondary vertices (in red) of the two b quarks decaying away from the primary vertex (in yellow). One of the bottom hadrons decays into a charm hadron that moves away from the secondary vertex before decaying ($b \to c \to X$; vertex in cyan).

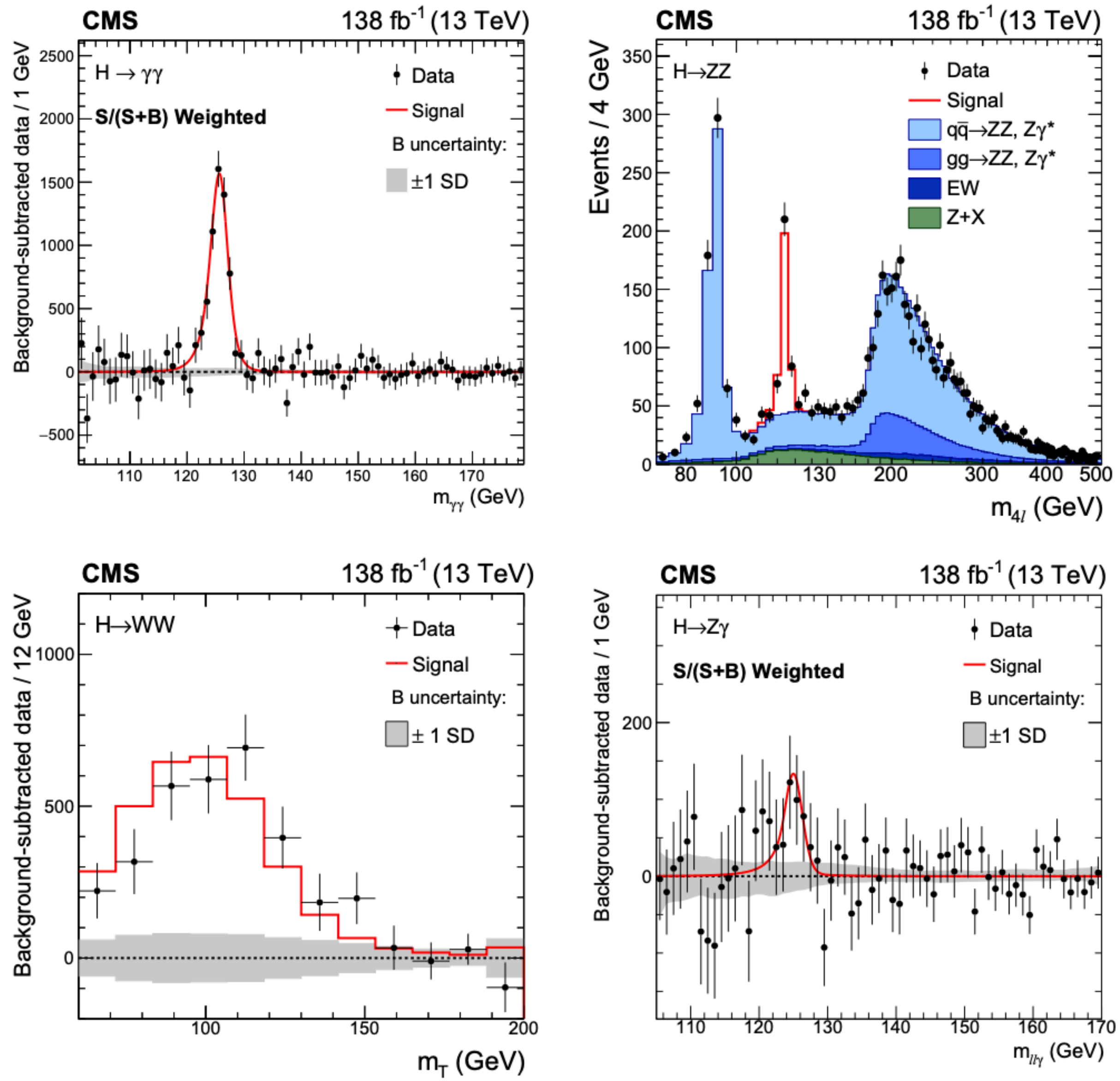


Figure B.3: **Higgs boson mass peak in diboson decay channels.**
(upper left) The background-subtracted diphoton invariant mass distribution targeting the study of the decay channel $\mathrm{H} \to \gamma\gamma$. (upper right) The invariant mass distribution of four charged leptons targeting the study of the decay channel $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$. (lower left) The background-subtracted transverse mass m_T distribution targeting the study of the decay channel $\mathrm{H} \to \mathrm{WW}$. (lower right) The background-subtracted $\ell\ell\gamma$ invariant mass distribution targeting the study of the decay channel $\mathrm{H} \to \mathrm{Z}\gamma$. The SM prediction for the signal (red line) is scaled by the value of μ, as estimated in the dedicated analysis for that channel, and computed for $m_\mathrm{H} = 125.38\,\mathrm{GeV}$. The grey band around zero shows the 1 s.d. uncertainty in the background subtraction.

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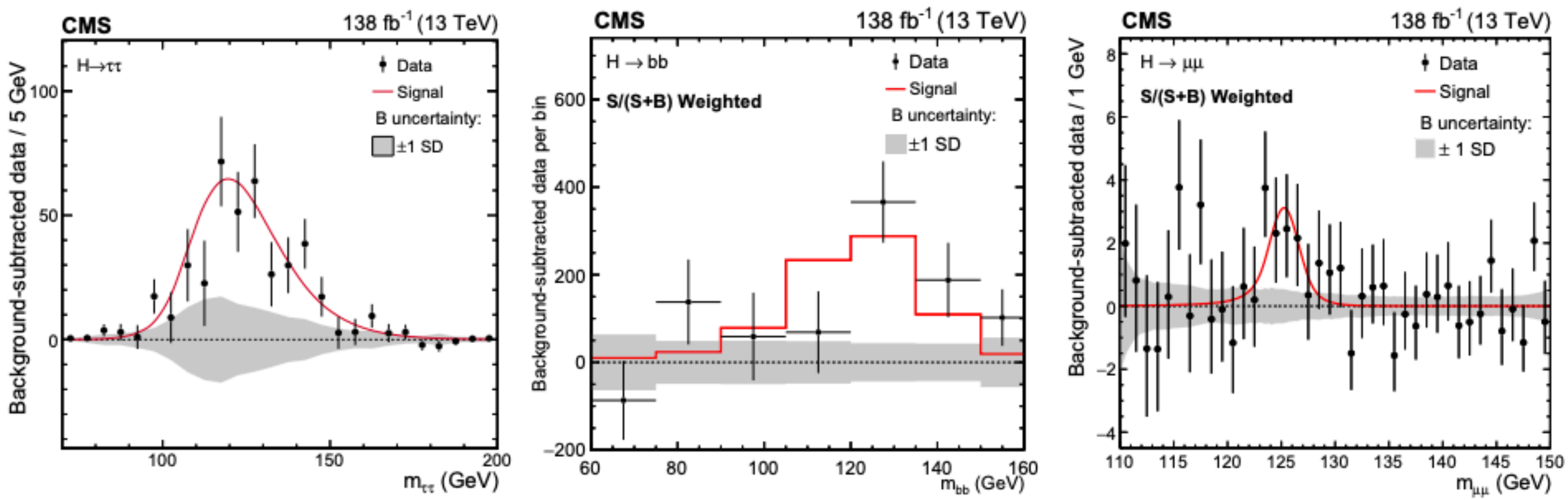


Figure B.4: **Higgs boson mass peak in difermion decay channels.**

The background-subtracted diparticle invariant mass distribution targeting the study of the decay channel (left) $H \to \tau\tau$, (center) $H \to bb$, (right) $H \to \mu\mu$. The SM prediction for the signal (red line) is scaled by the value of μ, as estimated in the dedicated analysis for that channel, and computed for $m_H = 125.38\,\mathrm{GeV}$. The grey band around zero shows the 1 s.d. uncertainty in the background subtraction.

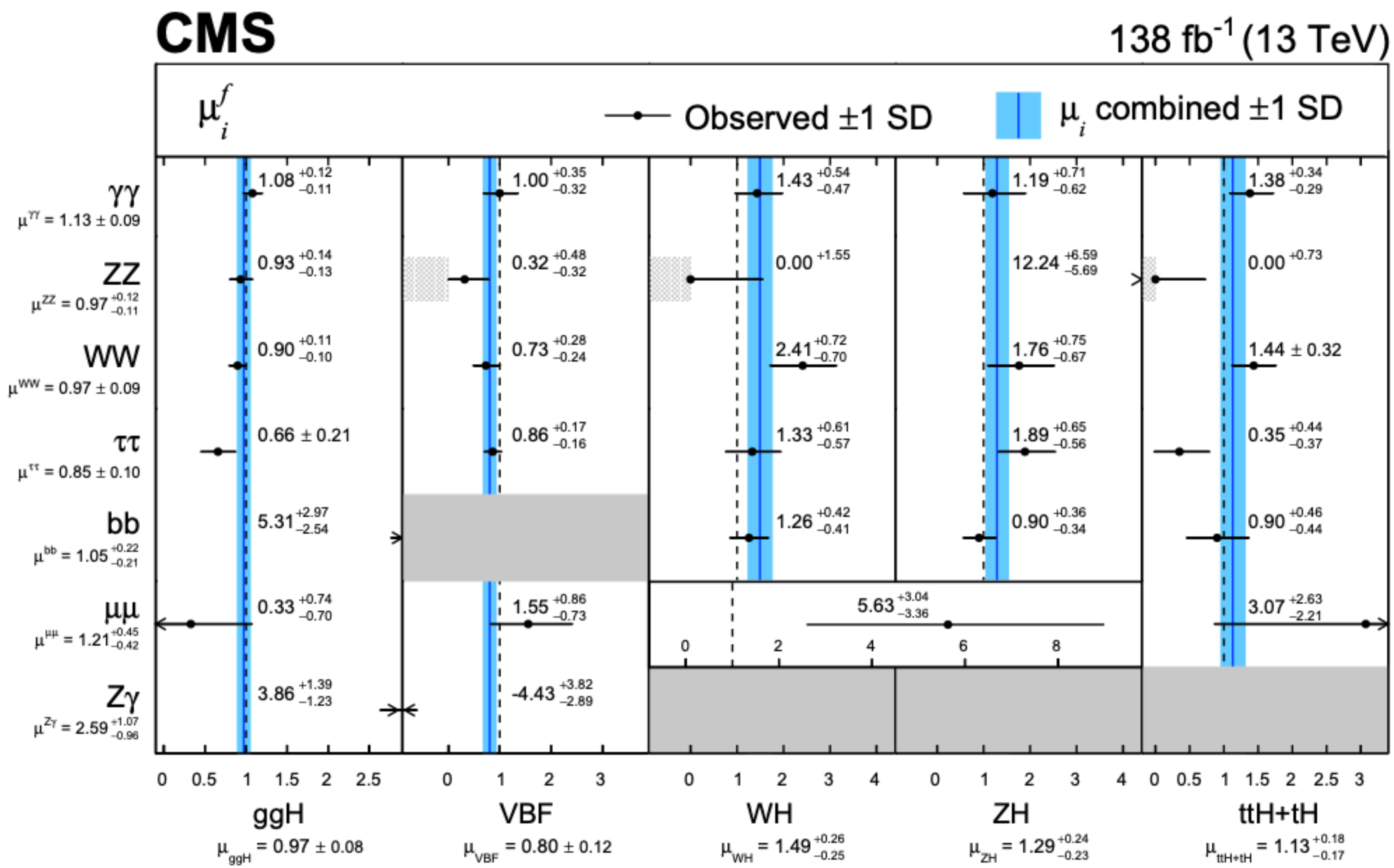
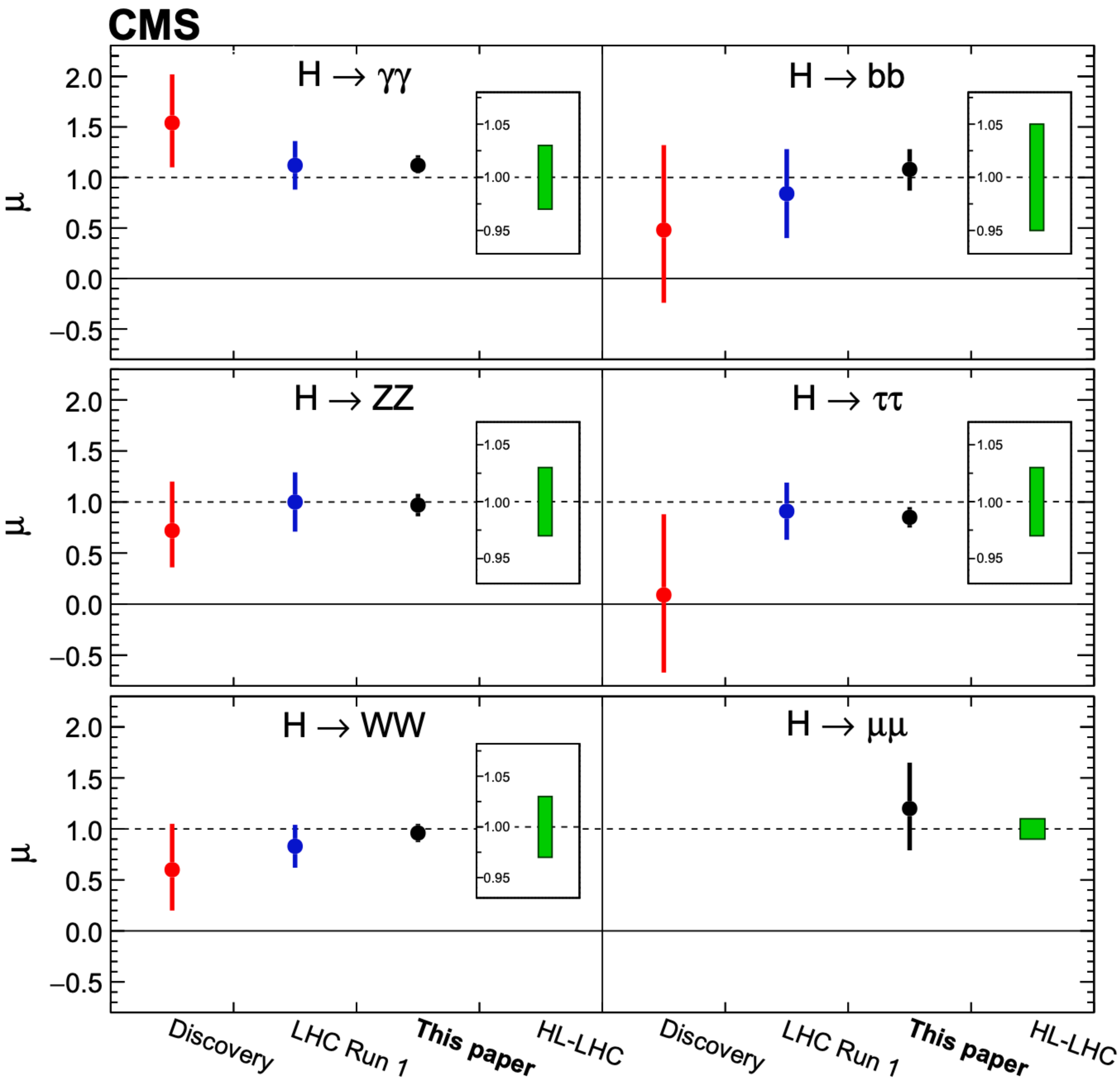


Figure B.6: **The agreement with the SM predictions in Higgs boson production and decay.**

Signal strength parameters per individual production mode and decay channel μ_i^f, and combined per production mode μ_i and decay channel μ^f. In this fit, ttH and tH are considered together and the μ_i results are slightly different from those of Fig. 2 (left). The dashed vertical lines at 1 represent the SM value. Light grey shading indicates that μ is contained to be positive. Dark grey shading indicates the absence of measurement. The p-value with respect to the SM prediction is 5.8%.



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Kappa framework

2.3. Signal strengths

The signal strength μ, defined as the ratio of the measured Higgs boson rate to its SM prediction, is used to characterise the Higgs boson yields. For a specific production process and decay mode $i \to H \to f$, the signal strengths for the production, μ_i, and for the decay, μ^f, are defined as

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{B}^f}{(\mathrm{B}^f)_{\mathrm{SM}}}. \tag{2}$$

Here σ_i ($i = gg\mathrm{F}, \mathrm{VBF}, WH, ZH, ttH$) and B^f ($f = ZZ, WW, \gamma\gamma, \tau\tau, bb, \mu\mu$) are respectively the production cross section for $i \to H$ and the decay branching fraction for $H \to f$. The subscript "SM" refers to their respective SM predictions, so by definition, $\mu_i = 1$ and $\mu^f = 1$ in the SM. Since σ_i and B^f cannot be separated without additional assumptions, only the product of μ_i and μ^f can be measured experimentally, leading to a signal strength μ_i^f for the combined production and decay:

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f. \tag{3}$$

2.4. Coupling modifiers

Based on a LO-motivated framework [32] (κ-framework), coupling modifiers have been proposed to interpret the LHC data by introducing specific modifications of the Higgs boson couplings related to BSM physics. Within the assumptions already mentioned in Section 1, the production and decay of the Higgs boson can be factorised, such that the cross section times branching fraction of an individual channel $\sigma(i \to H \to f)$ contributing to a measured signal yield can be parameterised as:

$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}, \tag{4}$$

where Γ_H is the total width of the Higgs boson and Γ^f is the partial width for Higgs boson decay to the final state f. A set of coupling modifiers, $\vec{\kappa}$, is introduced to parameterise possible deviations from the SM predictions of the Higgs boson couplings to SM bosons and fermions. For a given production process or decay mode, denoted "j", a coupling modifier κ_j is defined such that:

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}}, \tag{5}$$

Table 4: Higgs boson production cross sections σ_i, partial decay widths Γ^f, and total decay width (in the absence of BSM decays) parameterised as a function of the κ coupling modifiers as discussed in the text, including higher-order QCD and EW corrections to the inclusive cross sections and decay partial widths. The coefficients in the expression for Γ_H do not sum exactly to unity because some contributions that are negligible or not relevant to the analyses presented in this paper are not shown.

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(VBF)$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

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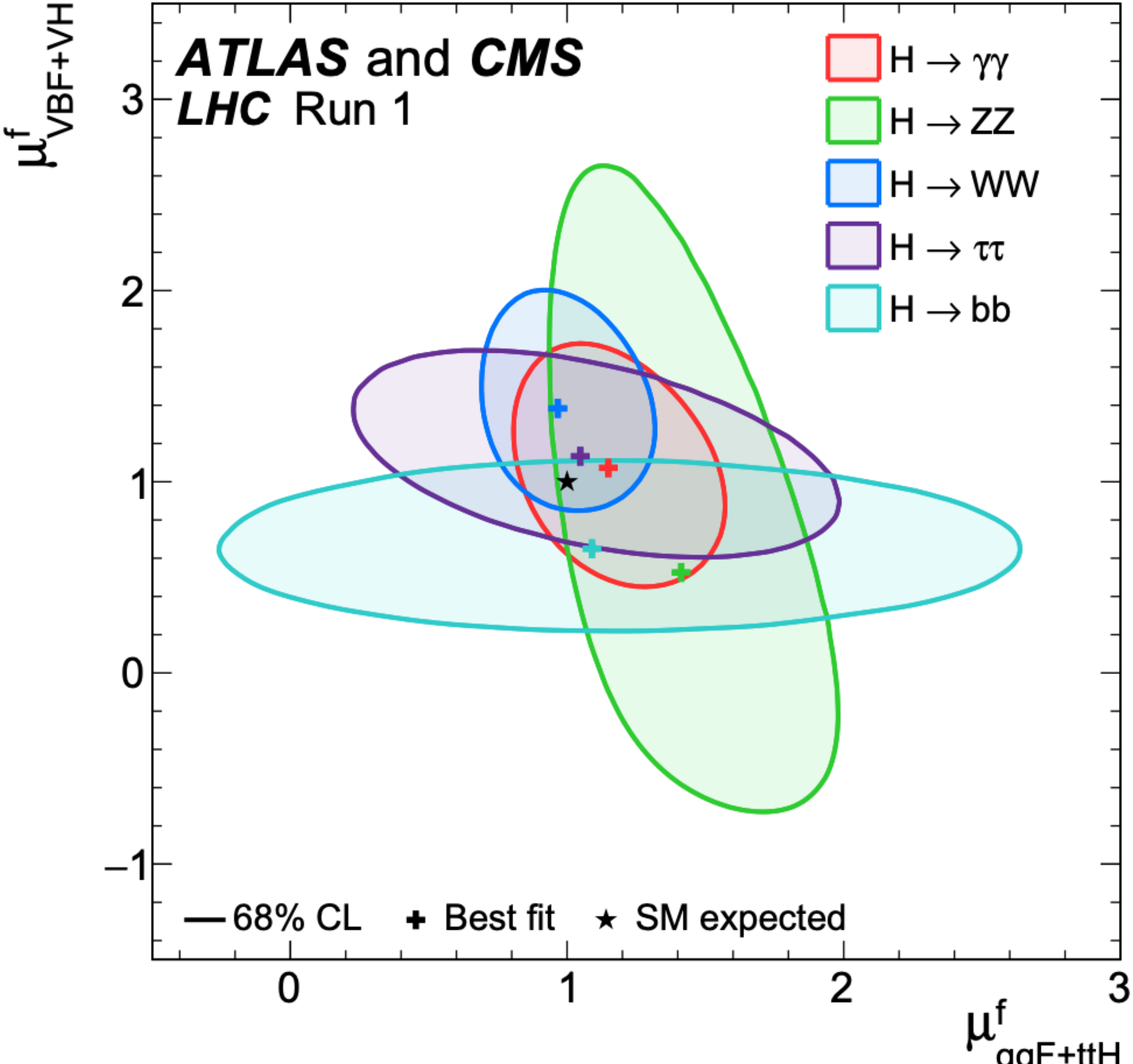
Changes in the values of the couplings will result in a variation of the Higgs boson width. A new modifier, κ_H, defined as $\kappa_H^2 = \sum_j B_{SM}^j \kappa_j^2$ and assumed to be positive without loss of generality, is introduced to characterise this variation. In the case where the SM decays of the Higgs boson are the only ones allowed, the relation $\kappa_H^2 = \Gamma_H/\Gamma_H^{SM}$ holds. If instead deviations from the SM are introduced in the decays, the width Γ_H can be expressed as:

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - B_{BSM}}, \tag{6}$$

where B_{BSM} indicates the total branching fraction into BSM decays. Such BSM decays can be of three types: decays into BSM particles that are invisible to the detector because they do not appreciably interact with ordinary matter, decays into BSM particles that are not detected because they produce event topologies that are not searched for, or modifications of the decay branching fractions into SM particles in the case of channels that are not directly measured, such as $H \to cc$. Although direct and indirect experimental constraints on the Higgs boson width exist, they are either model dependent or are not stringent enough to constrain the present fits, and are therefore not included in the combinations. Since Γ_H is not experimentally constrained in a model-independent manner with sufficient precision, only ratios of coupling strengths can be measured in the most generic parameterisation considered in the κ-framework.

Table 5: Overview of the decay channels analysed in this paper. The ttH production process, which has contributions from all decay channels, is also shown. To show the relative importance of the various channels, the results from the combined analysis presented in this paper for $m_H = 125.09$ GeV (Tables 12 and 13 in Section 5.2) are reported as observed signal strengths μ with their measured uncertainties. The expected uncertainties are shown in parentheses. Also shown are the observed statistical significances, together with the expected significances in parentheses, except for the $H \to \mu\mu$ channel, which has very low sensitivity. For most decay channels, only the most sensitive analyses are quoted as references, e.g. the ggF and VBF analyses for the $H \to WW$ decay channel or the VH analysis for the $H \to bb$ decay channel. Although not exactly the same, the results are close to those from the individual publications, in which slightly different values for the Higgs boson mass were assumed and in which the signal modelling and signal uncertainties were slightly different, as discussed in the text.

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ] from results in this paper (Section 5.2)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[92]	[93]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[94]	[95]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[96, 97]	[98]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[99]	[100]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[101]	[102]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[103]	[104]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[78, 105, 106]	[108]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)



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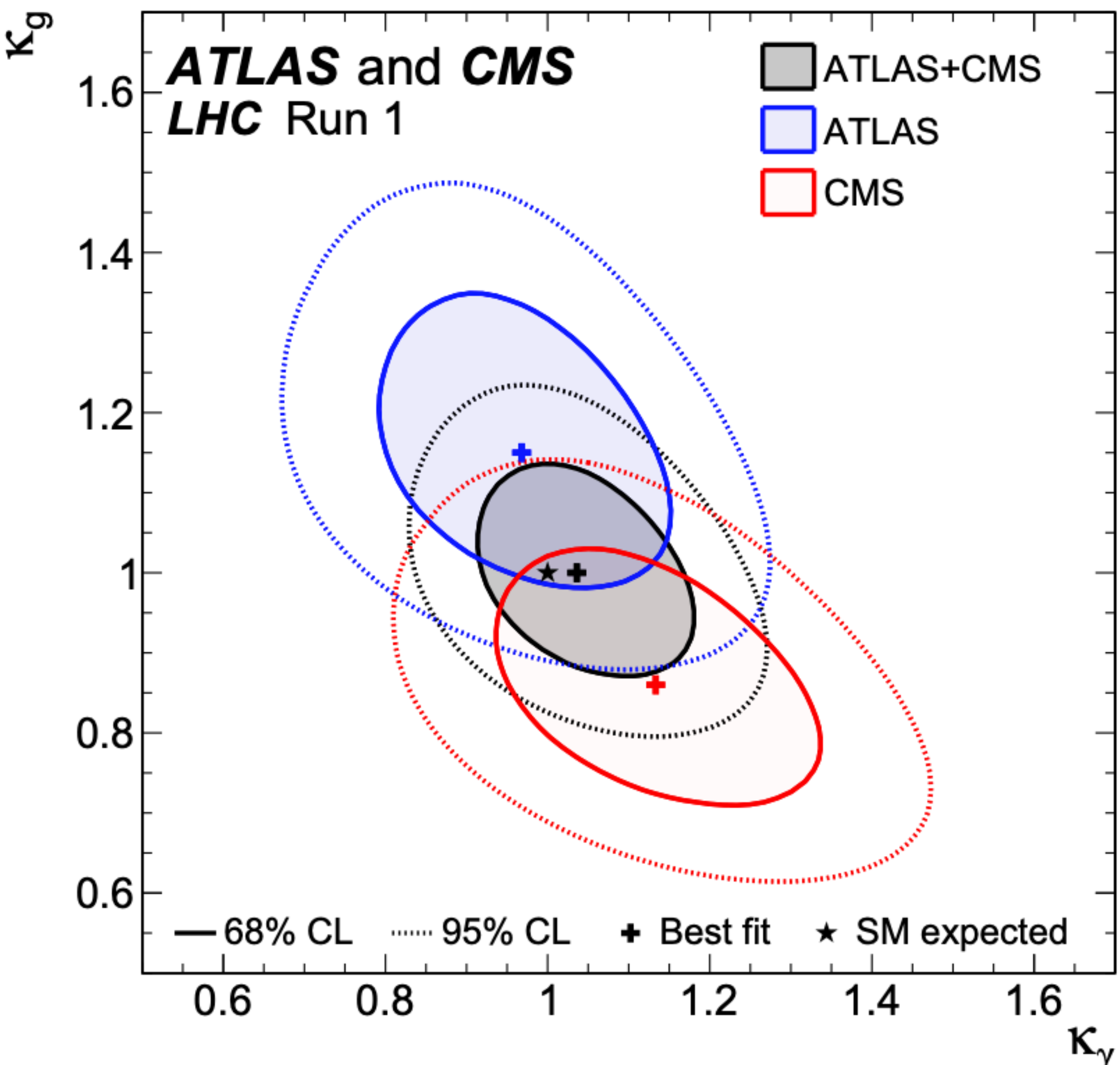

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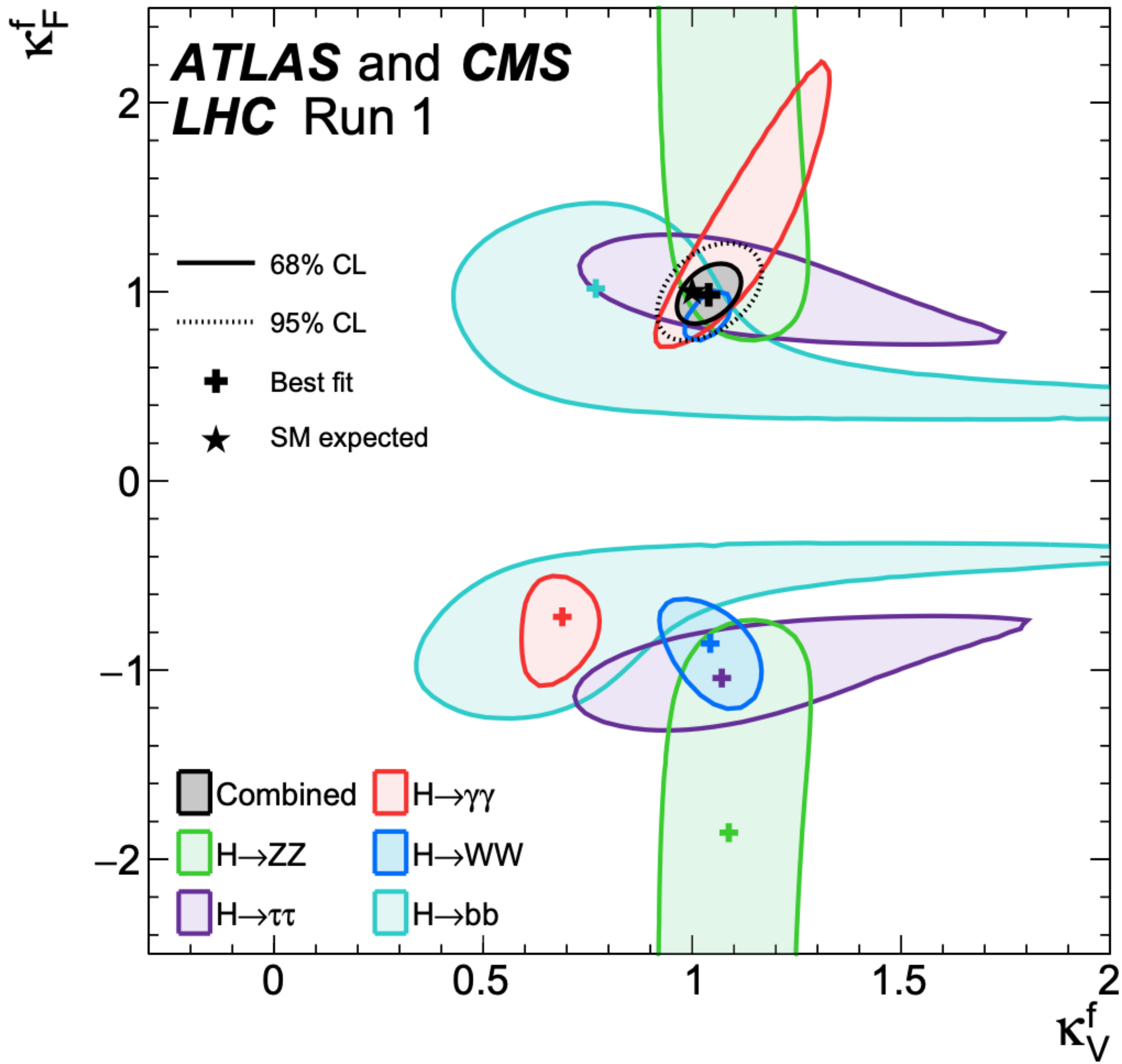

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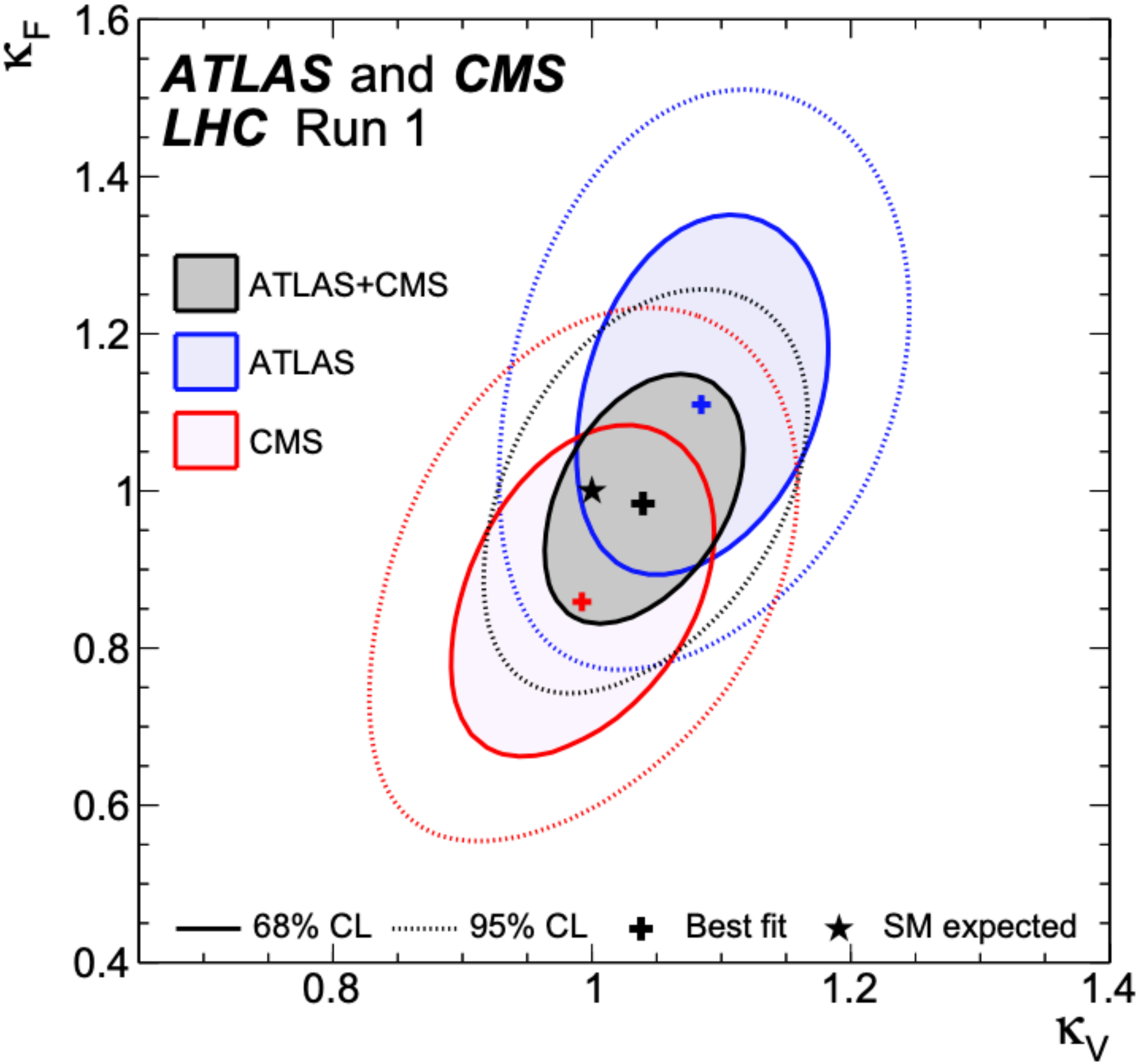

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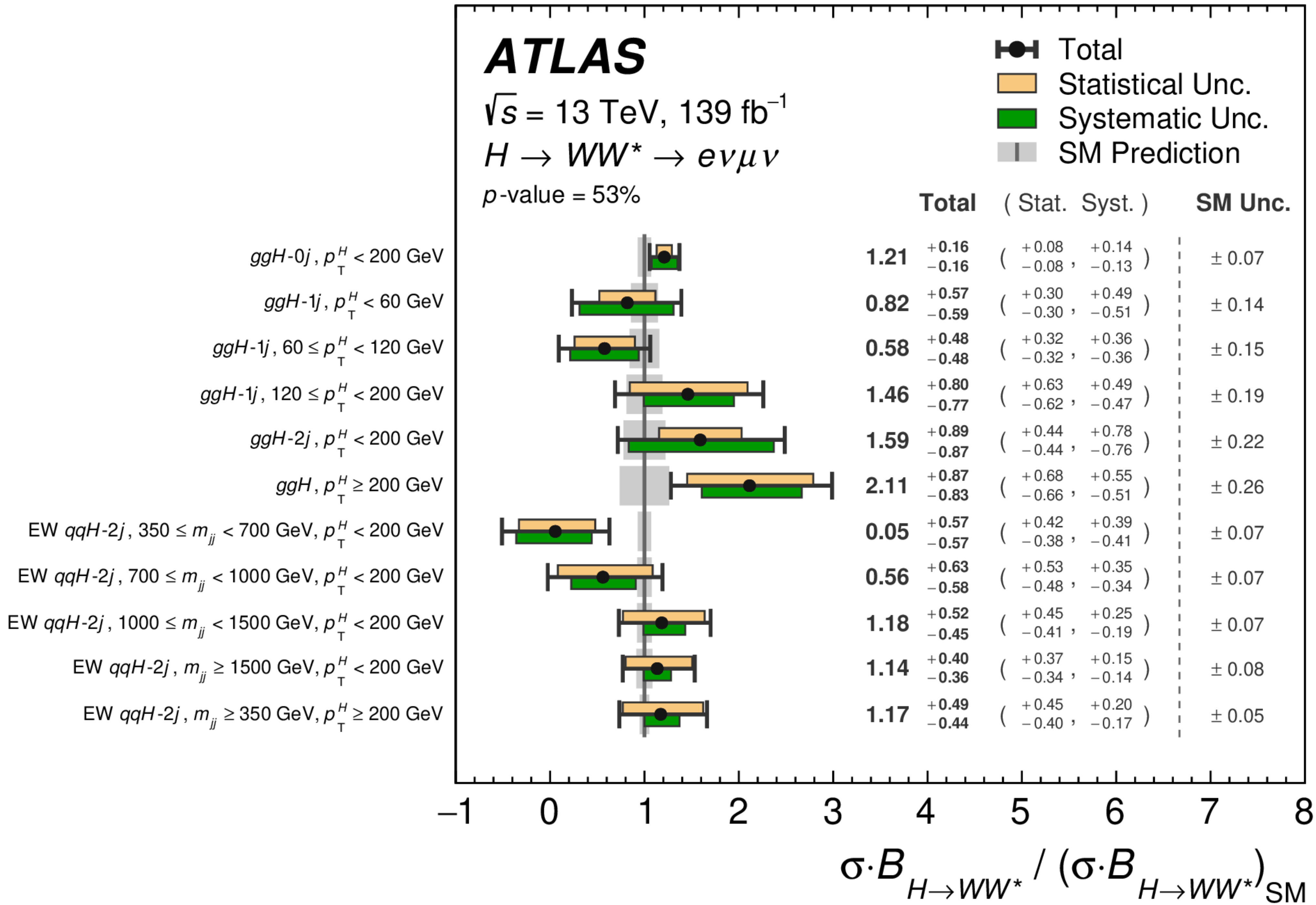
ATLAS
√s = 13 TeV, 139 fb⁻¹
H → WW* → eνμν
p-value = 53%
Total
Statistical Unc.
Systematic Unc.
SM Prediction
Total (Stat. Syst.) SM Unc.
ggH-0j, p_T^H < 200 GeV 1.21 +0.16 −0.16 (+0.08 −0.08 , +0.14 −0.13) ± 0.07
ggH-1j, p_T^H < 60 GeV 0.82 +0.57 −0.59 (+0.30 −0.30 , +0.49 −0.51) ± 0.14
ggH-1j, 60 ≤ p_T^H < 120 GeV 0.58 +0.48 −0.48 (+0.32 −0.32 , +0.36 −0.36) ± 0.15
ggH-1j, 120 ≤ p_T^H < 200 GeV 1.46 +0.80 −0.77 (+0.63 −0.62 , +0.49 −0.47) ± 0.19
ggH-2j, p_T^H < 200 GeV 1.59 +0.89 −0.87 (+0.44 −0.44 , +0.78 −0.76) ± 0.22
ggH, p_T^H ≥ 200 GeV 2.11 +0.87 −0.83 (+0.68 −0.66 , +0.55 −0.51) ± 0.26
EW qqH-2j, 350 ≤ m_jj < 700 GeV, p_T^H < 200 GeV 0.05 +0.57 −0.57 (+0.42 −0.38 , +0.39 −0.41) ± 0.07
EW qqH-2j, 700 ≤ m_jj < 1000 GeV, p_T^H < 200 GeV 0.56 +0.63 −0.58 (+0.53 −0.48 , +0.35 −0.34) ± 0.07
EW qqH-2j, 1000 ≤ m_jj < 1500 GeV, p_T^H < 200 GeV 1.18 +0.52 −0.45 (+0.45 −0.41 , +0.25 −0.19) ± 0.07
EW qqH-2j, m_jj ≥ 1500 GeV, p_T^H < 200 GeV 1.14 +0.40 −0.36 (+0.37 −0.34 , +0.15 −0.14) ± 0.08
EW qqH-2j, m_jj ≥ 350 GeV, p_T^H ≥ 200 GeV 1.17 +0.49 −0.44 (+0.45 −0.40 , +0.20 −0.17) ± 0.05
−1 0 1 2 3 4 5 6 7 8
σ·B_H→WW* / (σ·B_H→WW*)_SM

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